RF Systems for the 3rd Generation Synchrotron Radiation Facilities

Lecture 12

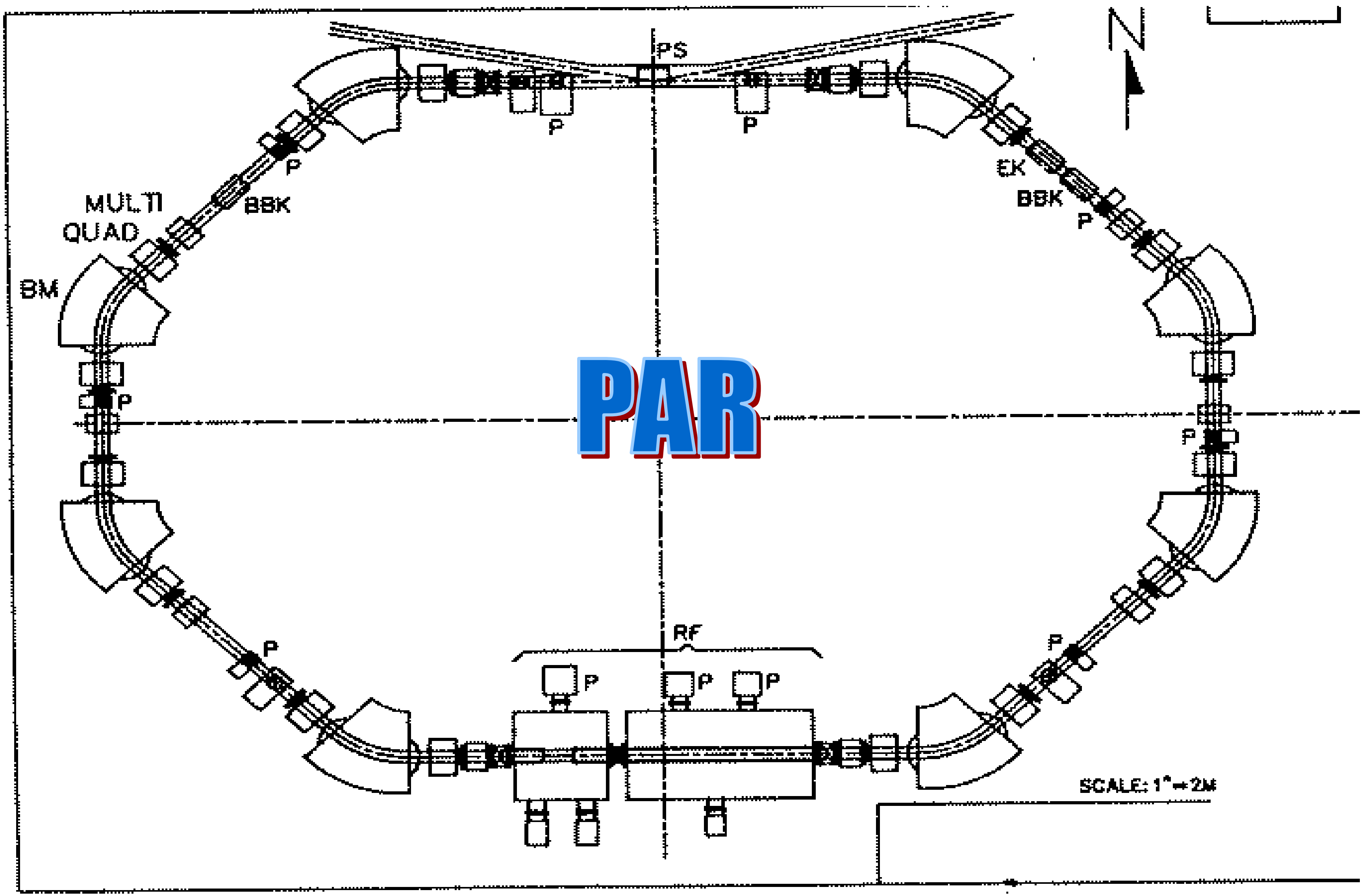
Accumulation Ring &Booster

February 11, 2003

Topics:

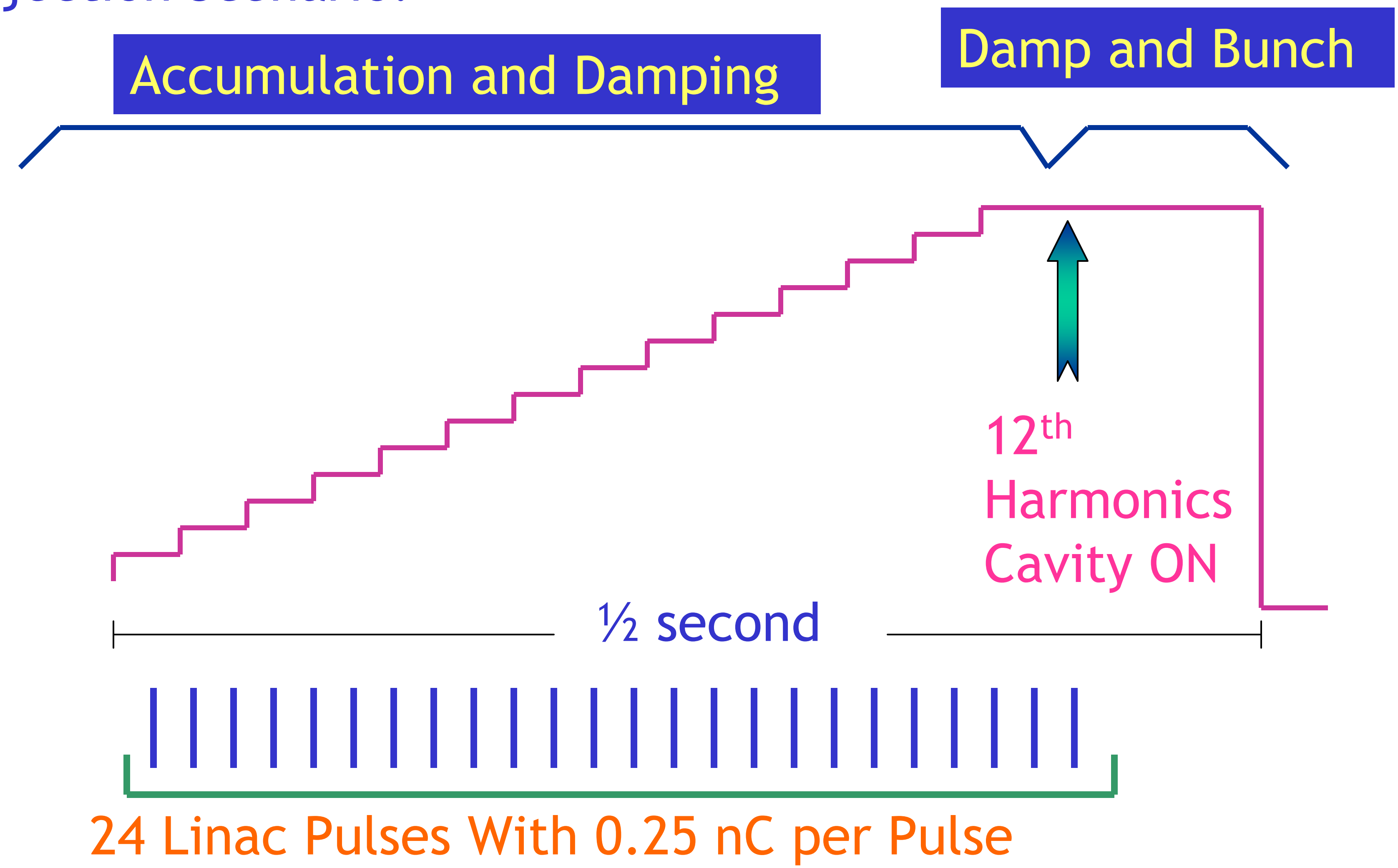
- Accumulation Ring
  - RF Bucket
  - Damping
  - Capture Cavity
  - Damping/Compression Cavity
- Booster Synchrotron
  - Injection
  - Ramping
  - RF Cavity

PAR Operation Cycle



PAR Operation Cycle

Injection Scenario:



PAR Operation Cycle

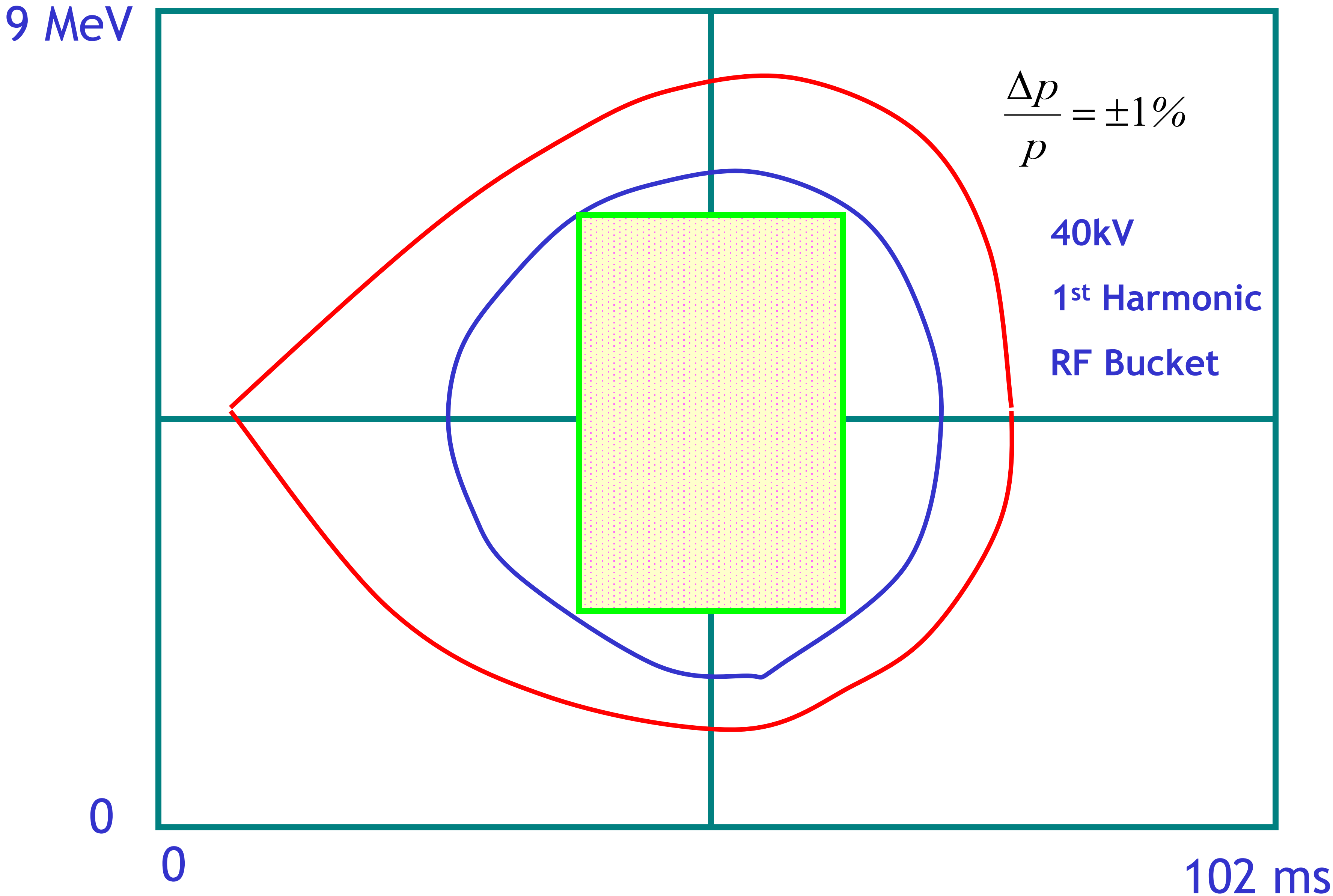
PAR cycle last 500 ms. At the beginning of the cycle, there in no stored beam, and only the first harmonic rf system (Fundamental Cavity) is on.

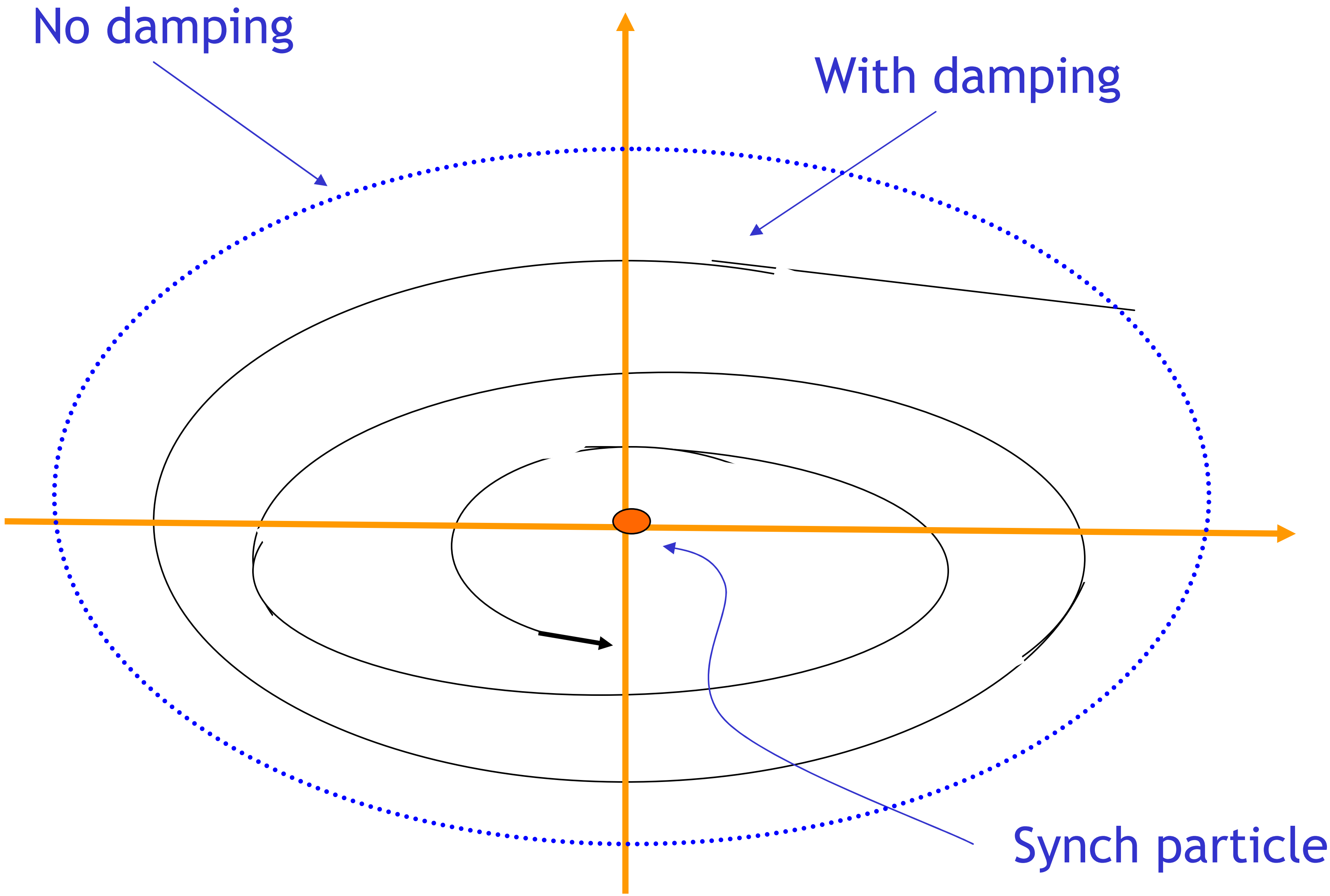
During the next 400 ms, 24 electron pulses (for example) from the linac are injected via LTP into the PAR.

After the last bunch train pulse is injected, the 12th harmonic rf system is turned on. During about 100 msec pf the cycle, the beam is damped by synchrotron radiation and compressed by the 12th harmonic cavity.

At the end of the cycle, the beam is ejected into the PTB for transport into the injector synchrotron.

PAR




No damping
With damping
Synch particle

PAR

The longitudinal phase space damping can be determined by

$$\frac{\sigma_E}{E(t)} = \sqrt{\left(\frac{\sigma_E}{E(\infty)}\right)^2 + \left(\frac{\sigma_E}{E(0)}\right)^2 - \left(\frac{\sigma_E}{E(\infty)}\right)^2 exp\left(-2t/\tau_E\right)}$$

is the natural (completely damped) energy spread in the ring.

During the 100 ms allowed for final damping, σ_E/E is reduced to the natural value of 0.4×10^{-3}. If the RF voltage remains at 40 kV, the final bunch length is σ_τ =0.92 ns, which is 1/3 of the 352 MHz injector synchrotron bucket.

I.S bucket = $\pm 1.55\,\sigma_\tau$

PAR Operation Cycle

What do RF Systems do?

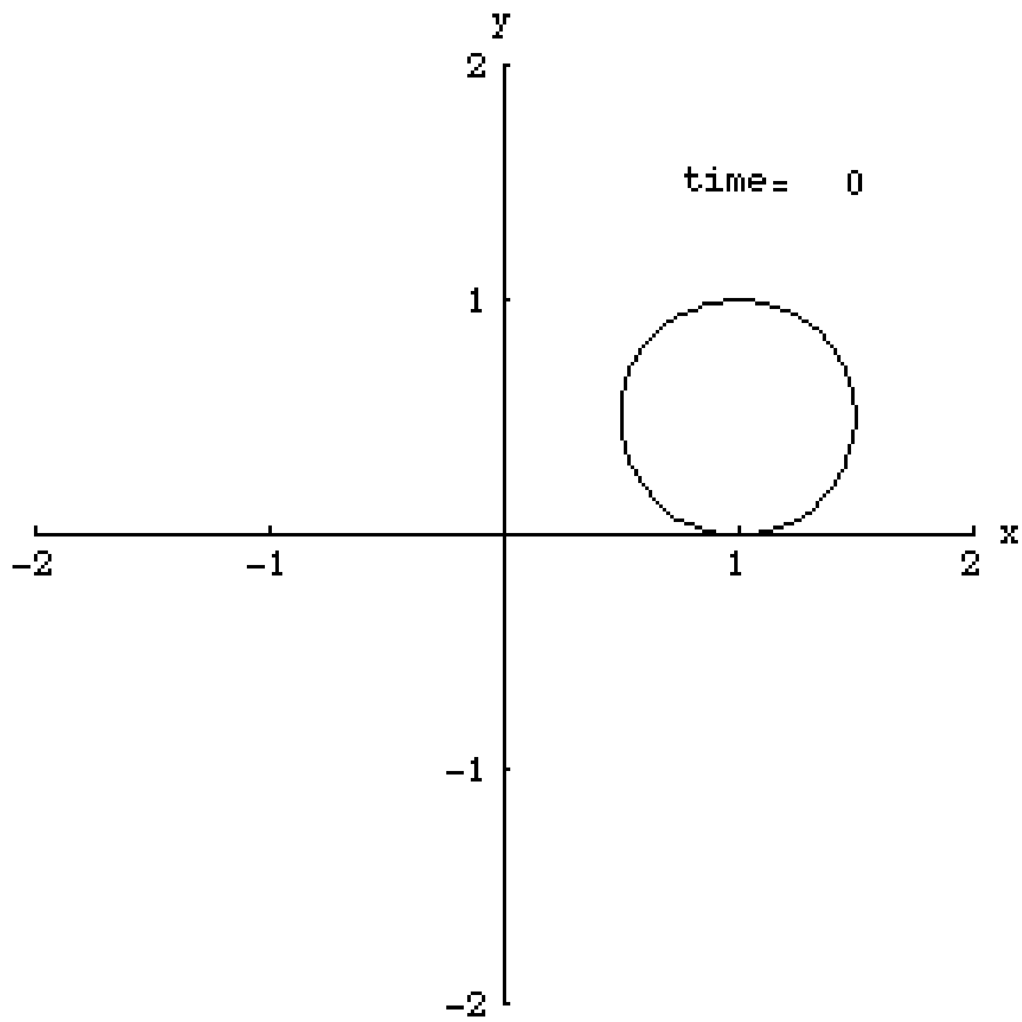
Fundamental (1st Harmonic) RF System

Restore the energy that electrons lose to synchrotron radiation

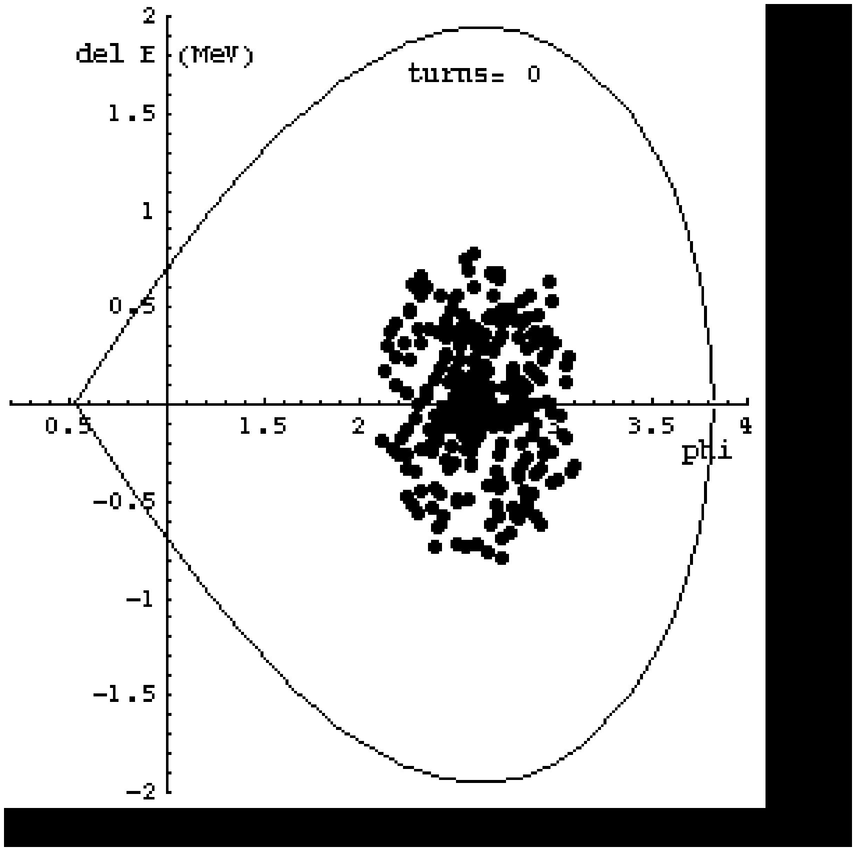
Perform most of the bunch length compression

12th Harmonic RF System

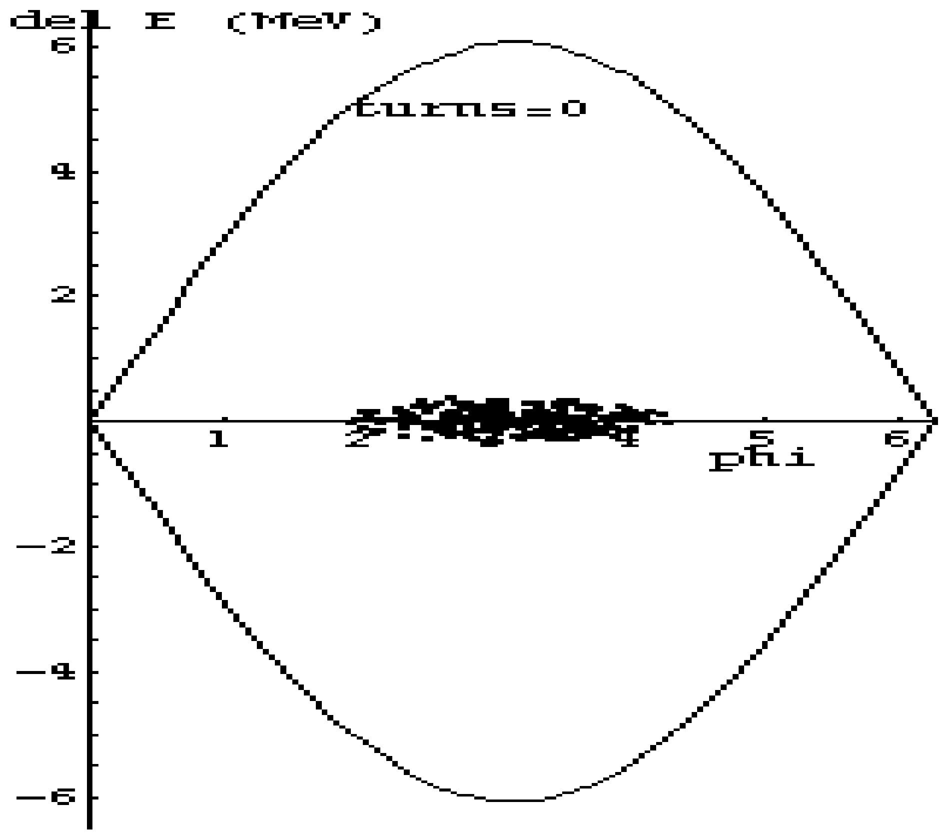
Complete compression of the bunch length



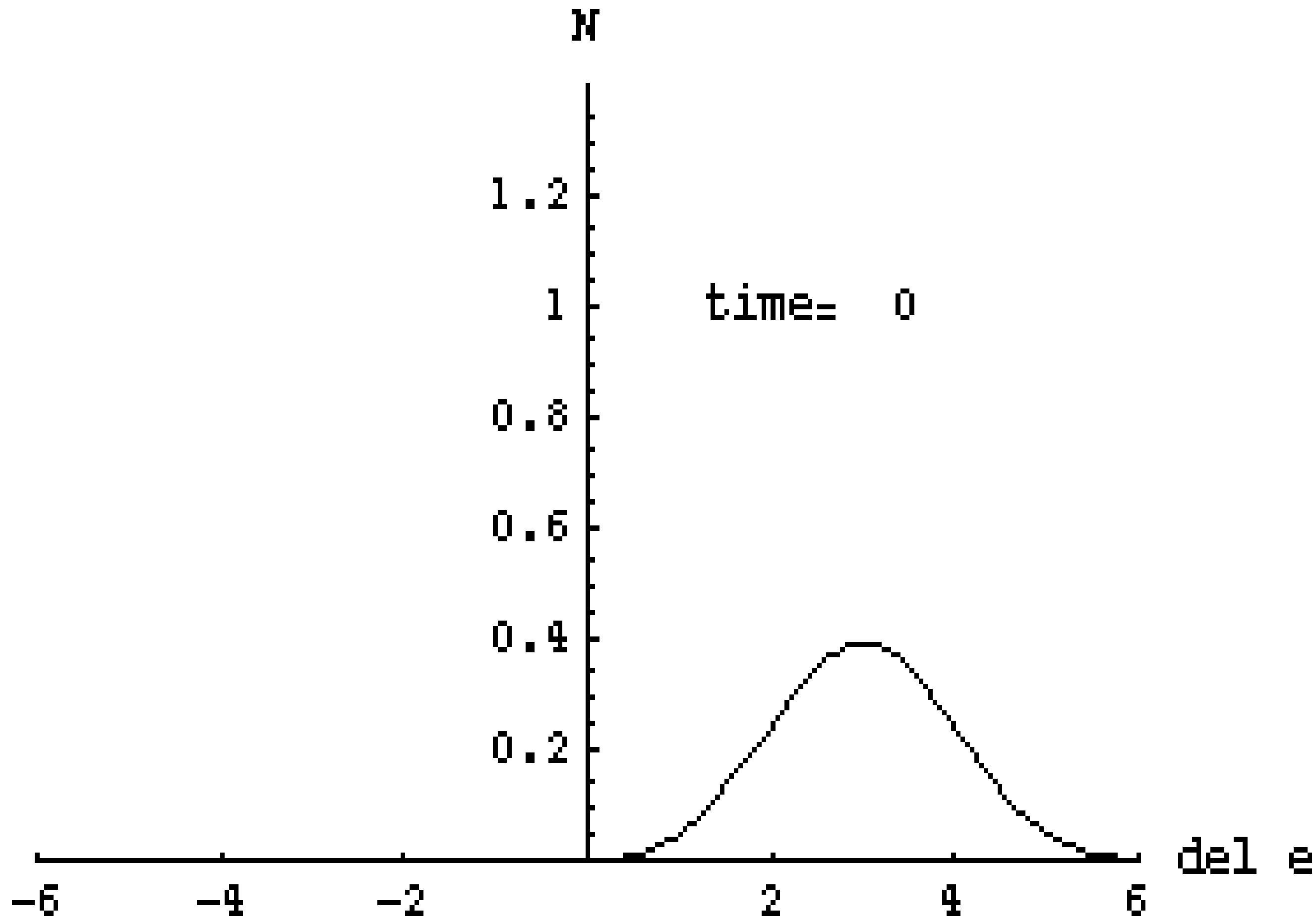
Injection Damping



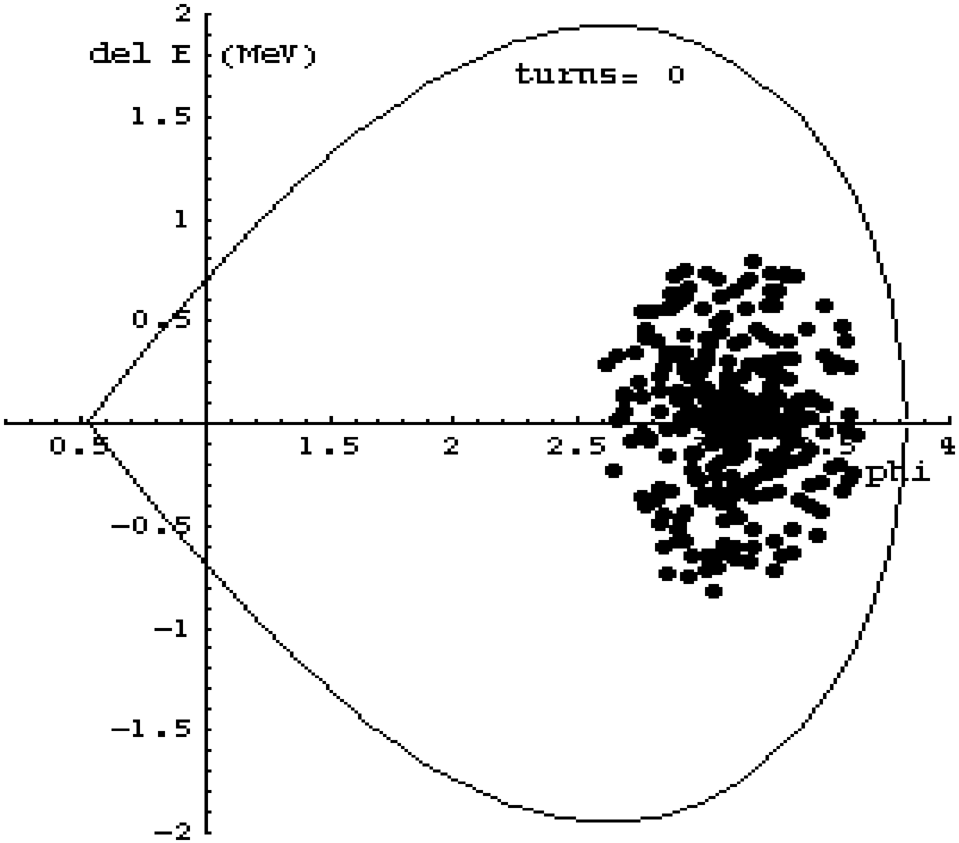
Evolution in the longitudinal phase space of a matched bunch in a bucket



Rotation in longitudinal phase space of a mismatched bunch



Damping of both the centroid and the width of an electron beam which is injected off-energy with an energy spread larger than the equilibrium energy spread.



Evolution in the longitudinal phase space of a bunch in a bucket with a 60 deg phase error

PAR

The bunch length damping provided by the 1st harmonic system is not adequate for efficient capture in the injector synchrotron. Therefore, a 12th harmonic 118 MHz, 30 kV system is needed for the final damping. This system is turned on after the last pulse.

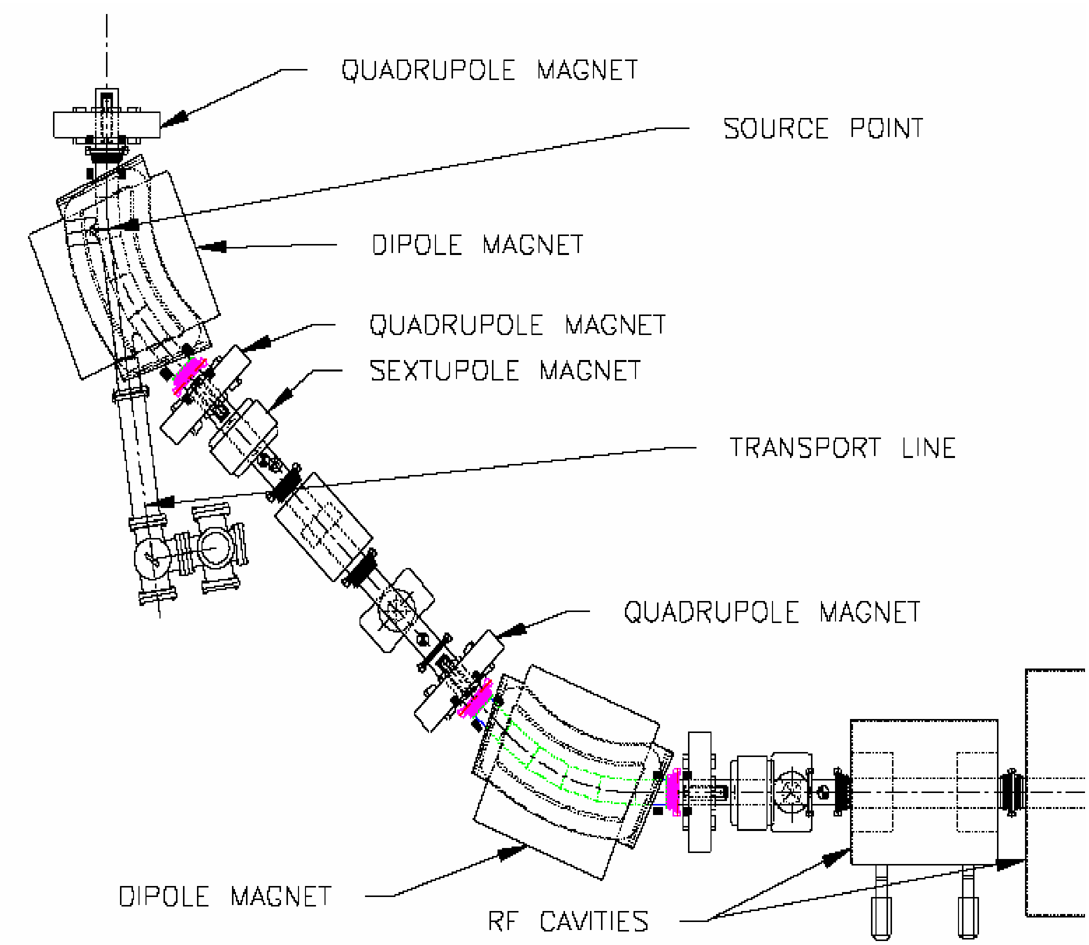
The first harmonic system damps the beam to

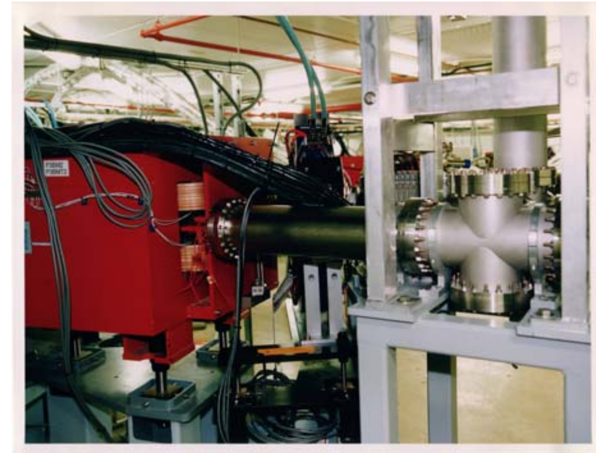
$$\sigma_E / E = 0.44 \times 10^{-3}$$
$$\sigma_\tau = 0.99\,ns$$

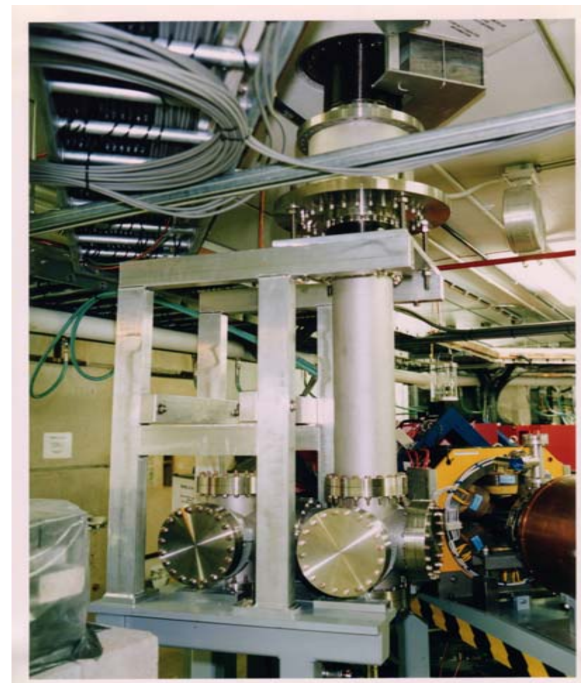
Final Bunch length

$$\sigma_E / E = 0.4 \times 10^{-3}$$
$$\sigma_\tau = 0.30\,ns$$

PAR

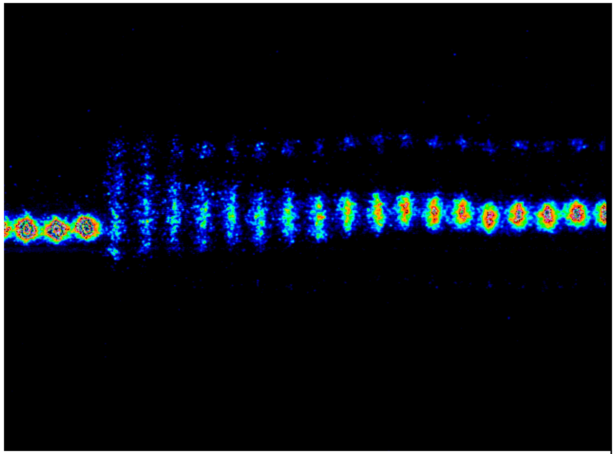

QUADRUPOLE MAGNET
SOURCE POINT
DIPOLE MAGNET
QUADRUPOLE MAGNET
SEXTUPOLE MAGNET
TRANSPORT LINE
QUADRUPOLE MAGNET
DIPOLE MAGNET
RF CAVITIES

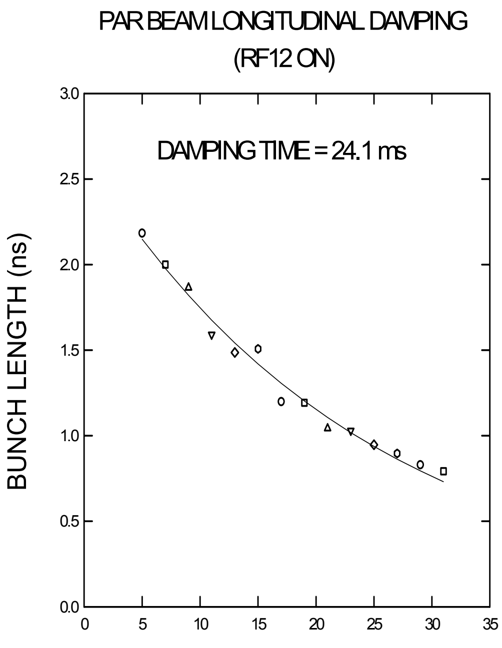


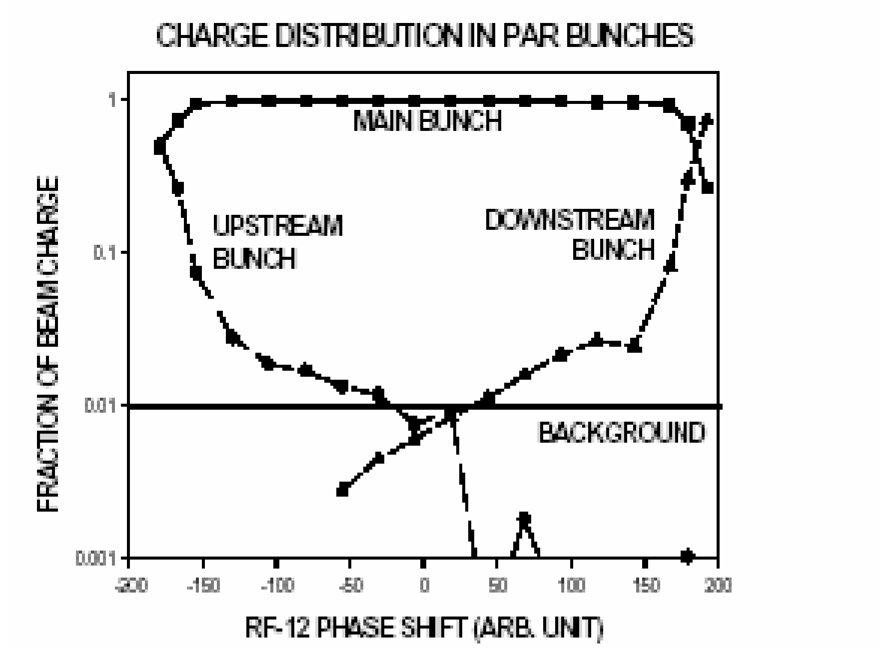


"B. Yang"

PAR



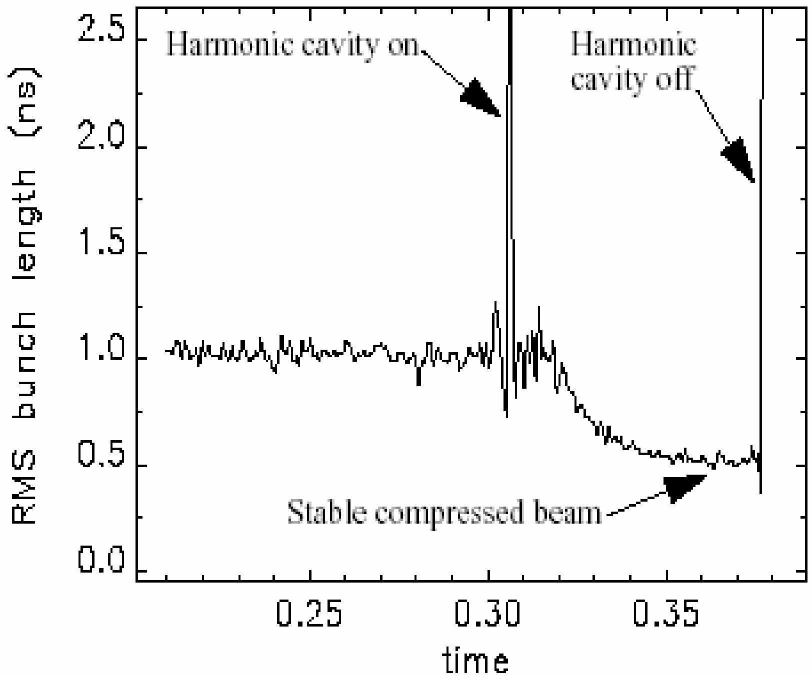




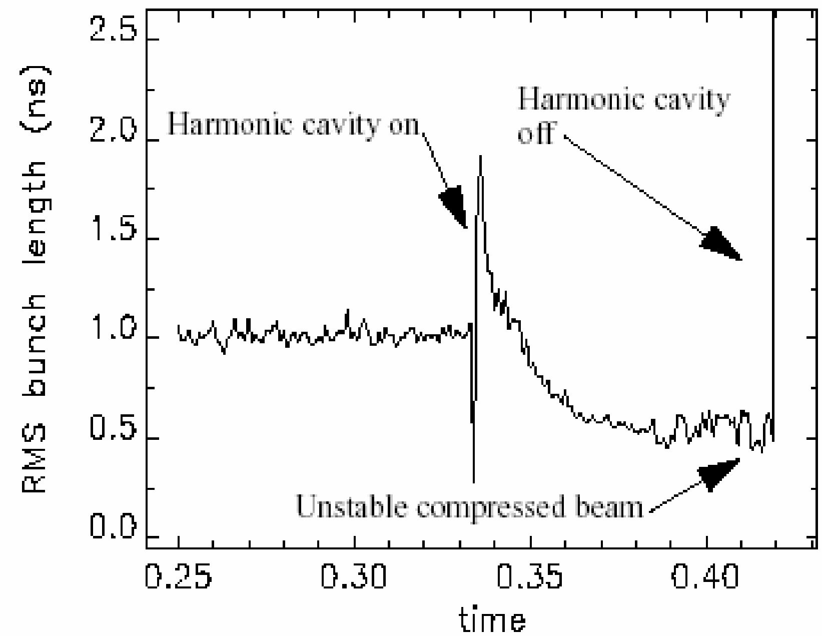
Intensity of bunches as a function of RF-12 phase. By varying the phase, one can minimize the satellite bunch intensity to a level acceptable to users.

"B. Yang"

PAR



Bunch Length vs Time for 4.8 nC Stored Charge



Bunch Length vs Time for 5.9 nC Stored Charge

Parameters for PAR RF Systems

System I

Frequency, f	9.77584	MHz
Harmonic number, h	1	
Peak Voltage V	40	kV
Synchrotron frequency f_s	19.0	kHz
Natural bunch length (damped)	0.92	ns

Parameters for PAR RF Systems

System II

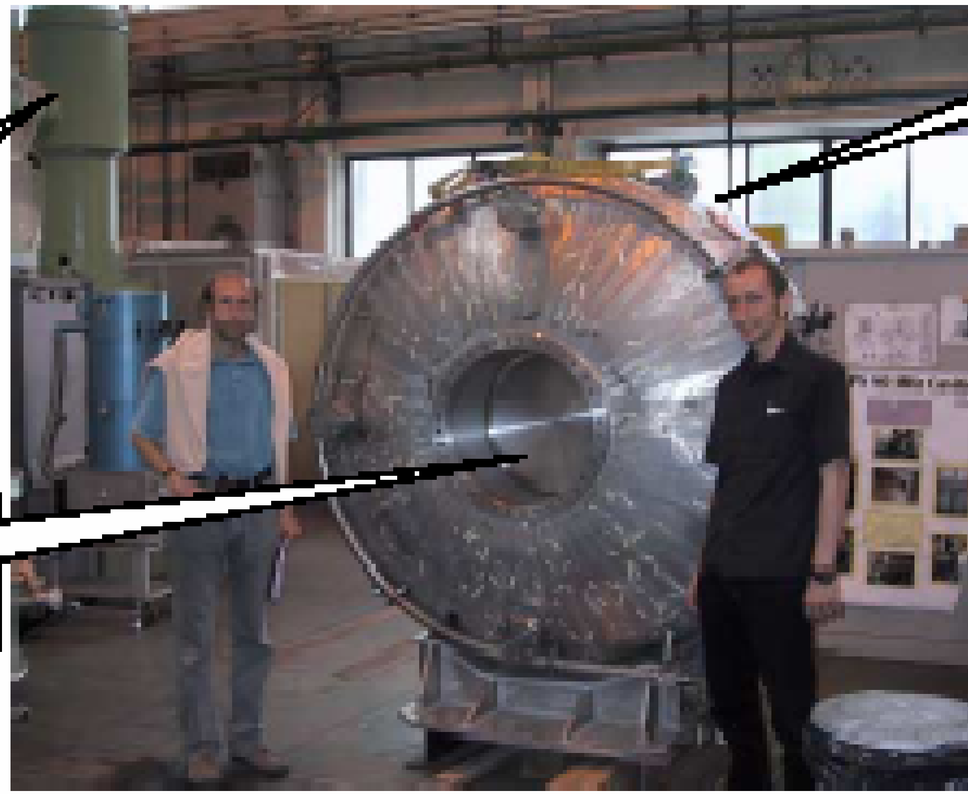
Frequency, f	117.3101	MHz
Harmonic number, h	12	
Peak Voltage $\boldsymbol{V}$	30	kV
Synchrotron frequency f_s	60.2	kHz
Natural bunch length (damped)	0.30	ns

Cavities RF Parameters

Parameter	1st Harmonic	12th Harmonic
Frequency, f (MHz)	9.77584	117. 3101
V (kV)	40	30
Type	$\lambda/4$, loaded	$\lambda/2$
$Z_o(\Omega)$ 50	50	50
Power (kW)	4.7	0.222
R_s (kΩ)	170	2020
Q	7630	25300

PAR RF Systems

88 MHz test cavity
(made from an 114 MHz structure)



H. Haseroth for the NF WG/CERN
Thursday, February 5-8, 2002

MUCOOL / MICE

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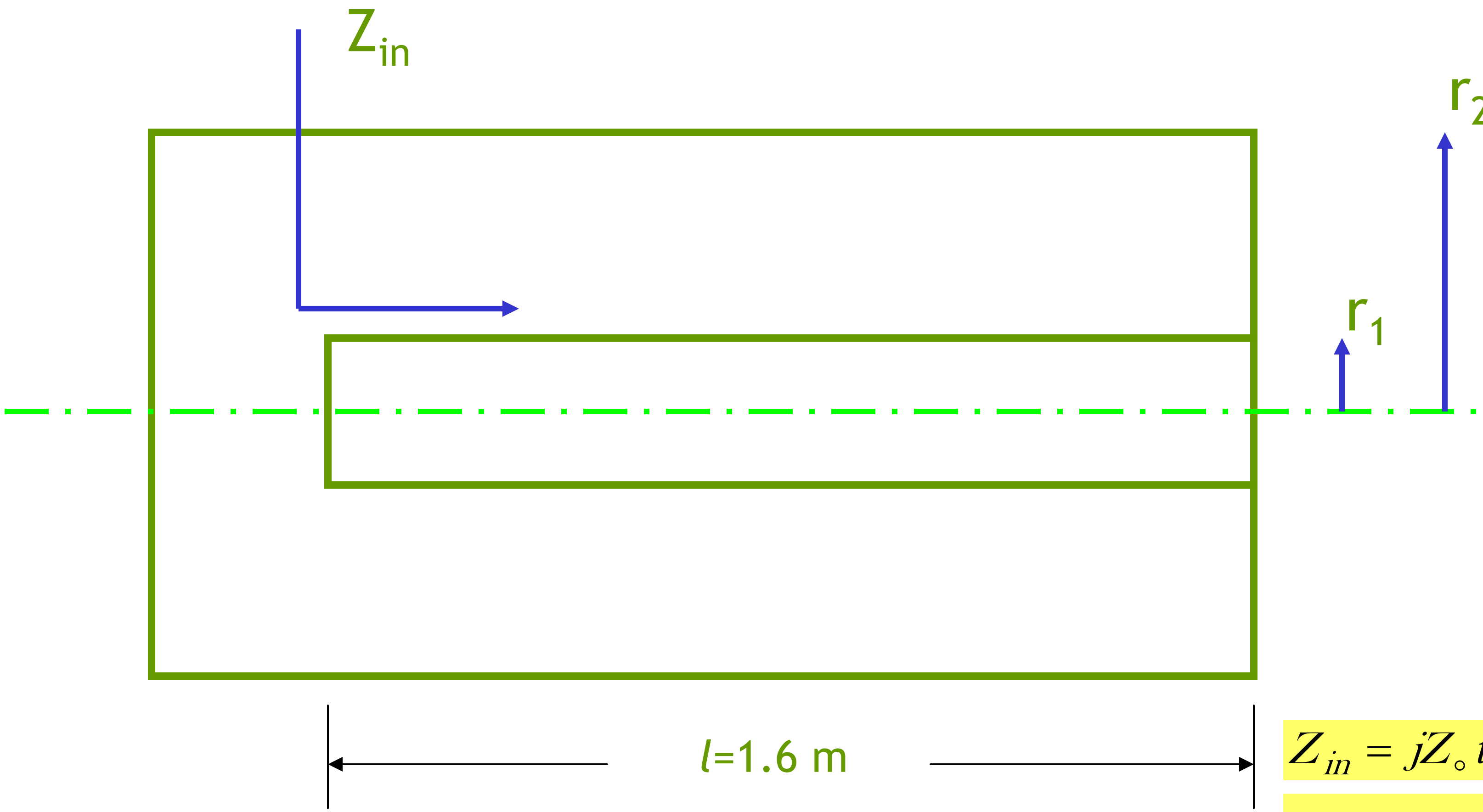
PAR RF Cavities

1st Harmonic (9.77584 MHz)

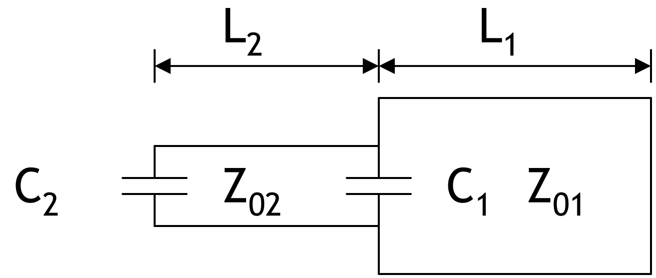


Diameter=1.2 m

$$Z_{in} = jZ_{\circ} \tan(\beta \ell)$$

$$Z_{\circ} = 60 \ln \frac{r_2}{r_1}$$

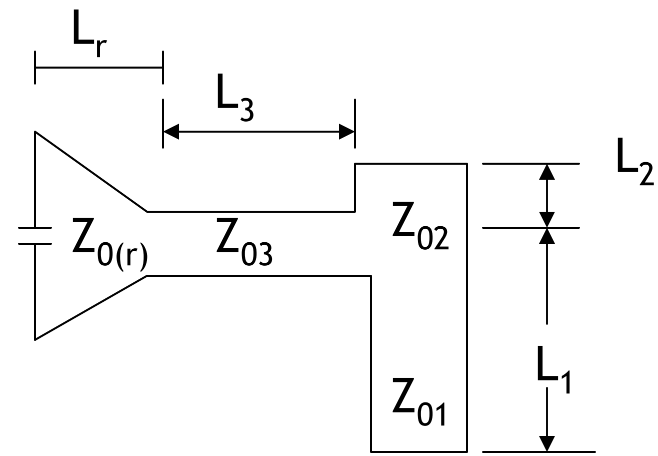
1^{st} Harmonic (9.77584 MHz)



Upper half of the folded coaxial cavity

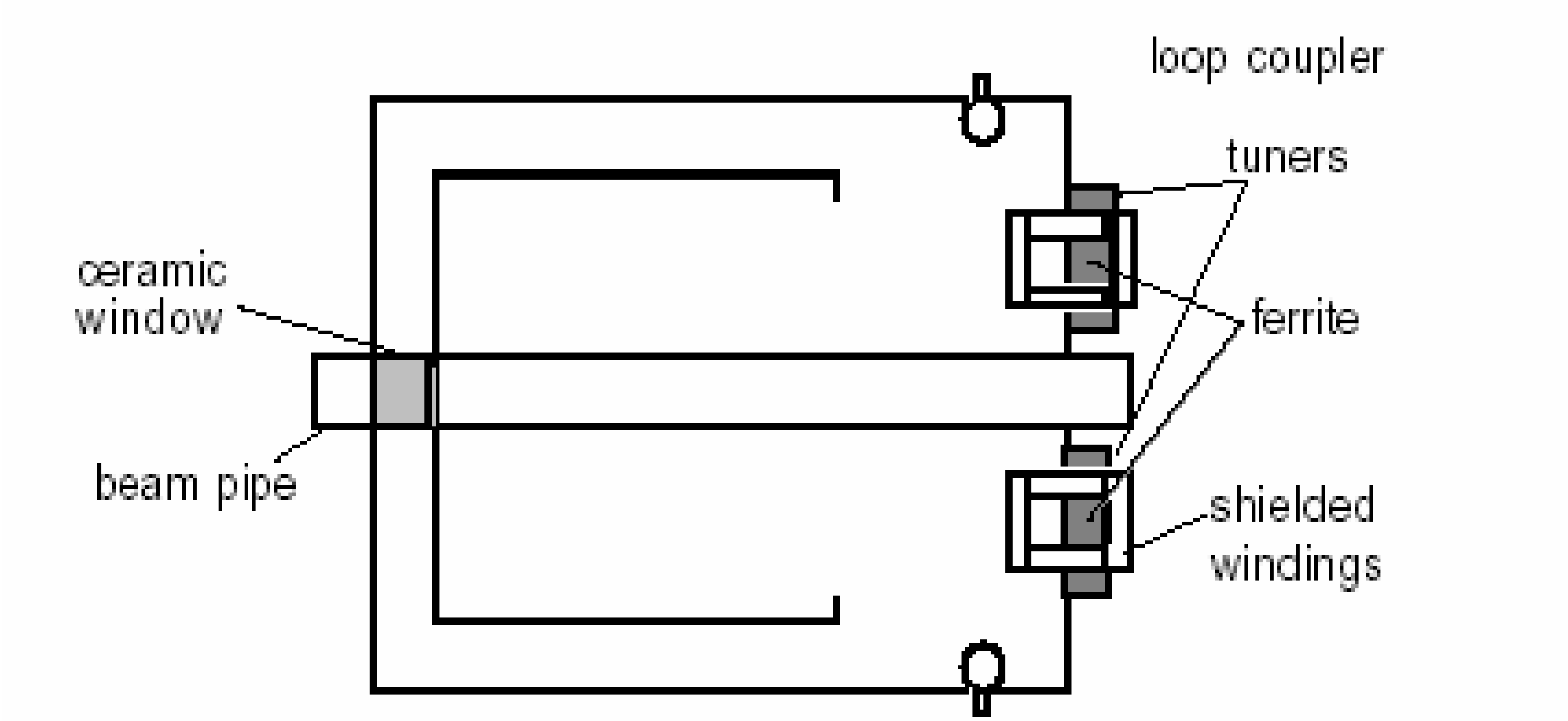
PAR RF Cavities

1st Harmonic (9.77584 MHz)



Radial Transmission Line Loaded Cavity

PAR RF Systems



PAR Fundamental Frequency Cavity

Radial Transmission Line

For the dominant TEM to r mode of a parallel plate radial transmission line structure, the fields with inward and outward traveling waves are

$$
\begin{aligned}
E_z &= AH_0^{(1)}(kr) + BH_0^{(2)}(kr) \\
&= \left[J_0^2(kr) + N_0^2(kr)\right]\left[Ae^{j\vartheta(kr)} + Be^{-j\vartheta(kr)}\right]
\end{aligned}
$$

$$
\begin{aligned}
H_\phi &= \frac{j}{\eta}\left[AH_1^{(1)}(kr) + BH_1^{(2)}(kr)\right] \\
&= \frac{\sqrt{J_0^2(kr) + N_0^2(kr)}}{Z_0^W(kr)}\left[Ae^{j\Psi(kr)} - Be^{-j\Psi(kr)}\right]
\end{aligned}
$$

Where A and B are magnitude of the incident and reflected waves, $H^{(1)}$ and $H^{(2)}$ are the Hankel functions of the first and second kind respectively.

$$
\left.
\begin{aligned}
H_n^{(1)} &= J_n + jN_n \\
H_n^{(2)} &= J_n - jN_n
\end{aligned}
\right]
$$

J_n is the n-th order Bessel function of the first kind and N_n is the n-th order Bessel function of the second kind.

Radial Transmission Line

$Z_o(kr)$ is the characteristic wave impedance of the radial transmission line:

$$Z_0^W(kr) = \eta\sqrt{\frac{J_0^2(kr)+N_0^2(kr)}{J_1^2(kr)+N_1^2(kr)}}$$

The phase functions are

$$\theta(v) = tan^{-1}\left[\frac{N_0(v)}{J_0(v)}\right]$$

$$\psi(v) = tan^{-1}\left[\frac{N_1(v)}{J_1(v)}\right]$$

Radial Transmission Line

The input impedance at a point r=r_i with a load impedance Z_L at r_L is

$$Z^b = Z_0(r_i)\frac{Z_L \cos\{\theta(kr_i)-\psi(kr_L)\}+jZ_0(r_L)\sin\{\theta(kr_i)-\theta(kr_L)\}}{Z_0(r_L)\cos\{\psi(kr_i)-\theta(kr_L)\}+jZ_L \sin\{\psi(kr_i)-\psi(kr_L)\}}$$

Where the characteristic impedance is give as

$$Z_0(r)=Z_0^W \frac{h}{2\pi r}$$

h line is the height of the radial transmission.

The electric field or voltage reflection coefficient at r=r_i in the radial transmission line section is

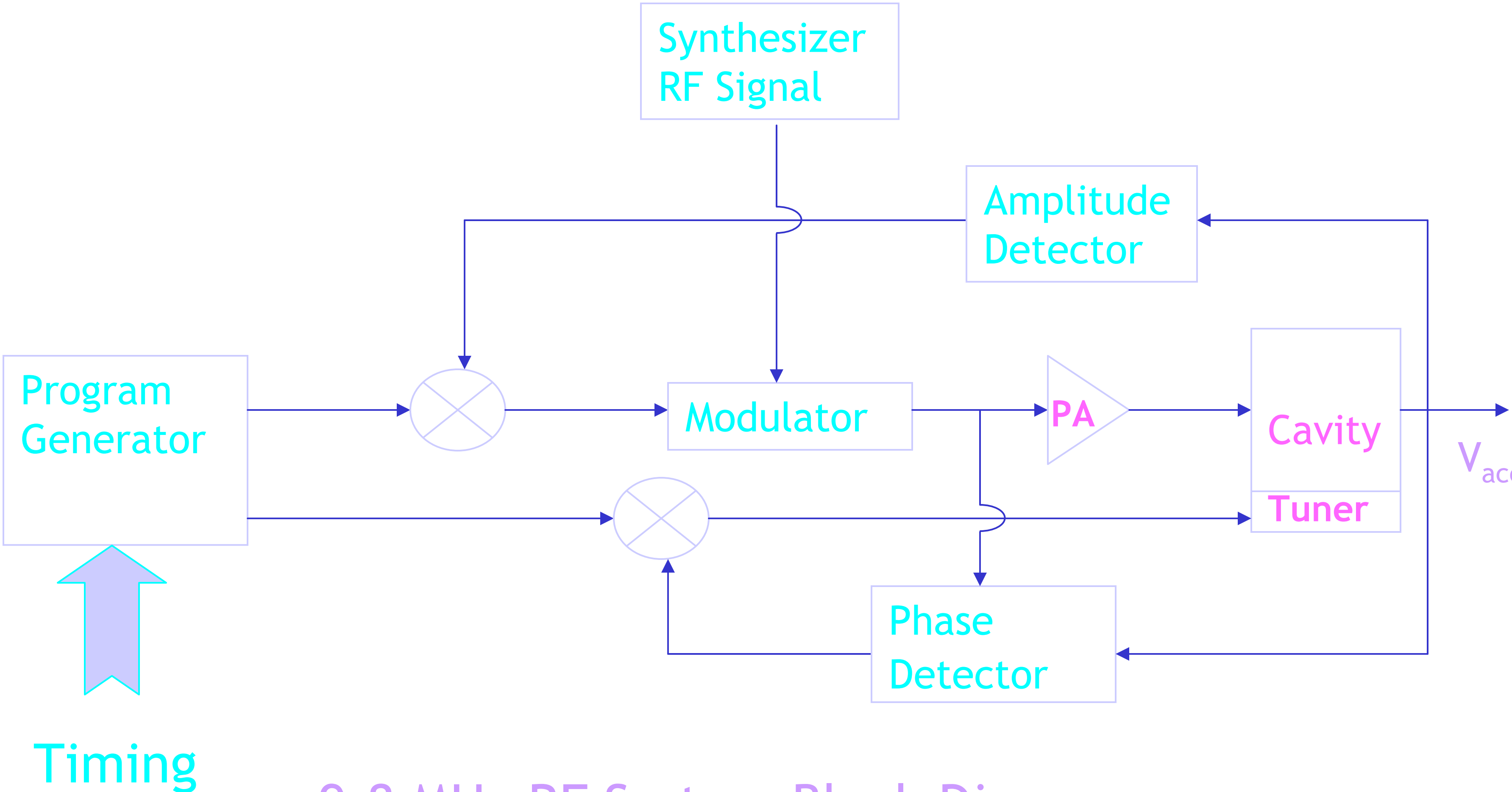
$$\Gamma(r_i)=\Gamma(r_L)e^{2j\{\theta(kr_i)-\theta(kr_L)\}}$$

The magnetic field or current reflection coefficient at r=r_i in the radial transmission line section is

$$\Gamma(r_i)=\Gamma(r_L)e^{2j\{\psi(kr_i)-\psi(kr_L)\}}$$

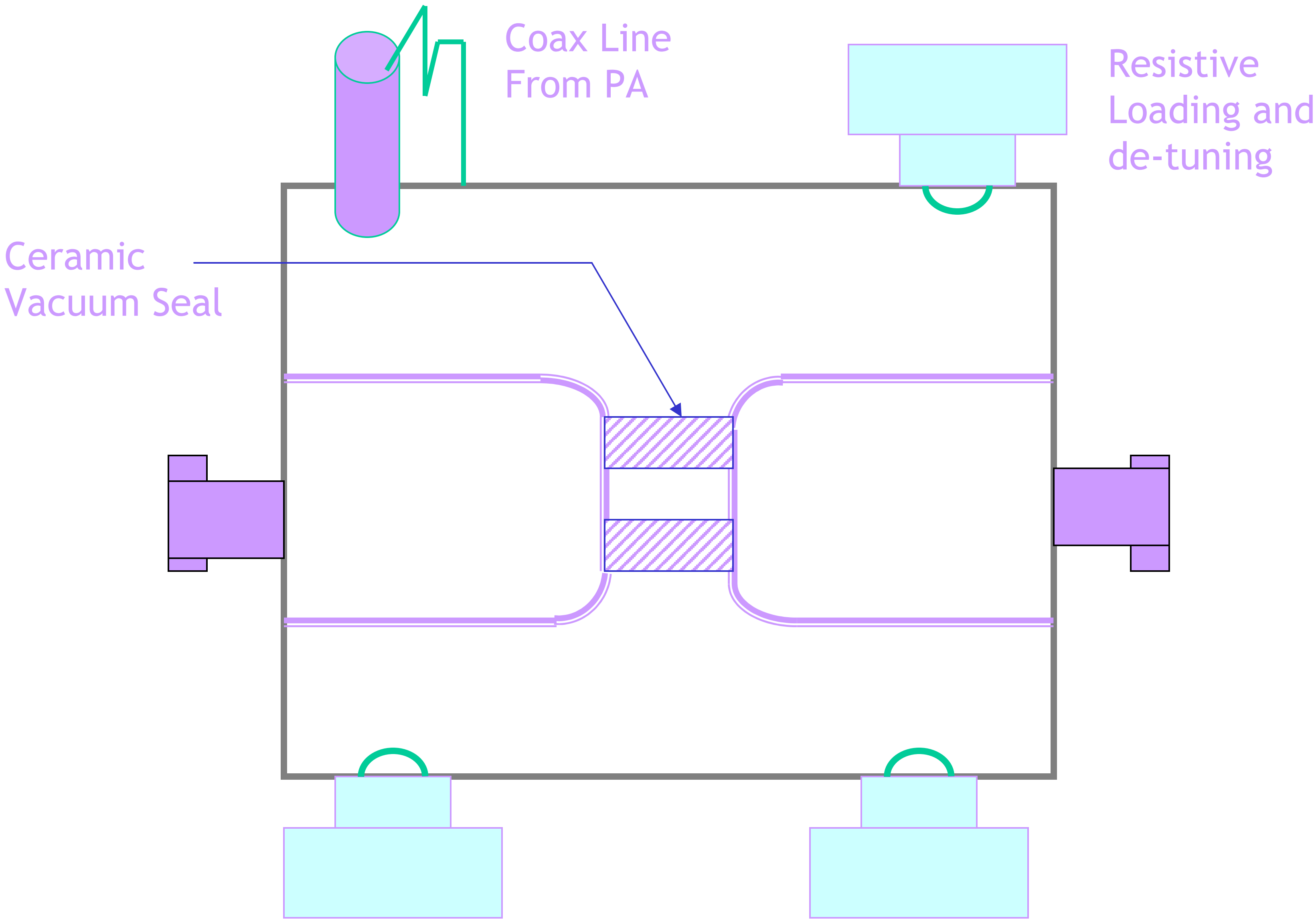
$$\Gamma(r_L)=\frac{Z_L-Z_0(r_L)}{Z_L+Z_0(r_L)}$$

PAR RF

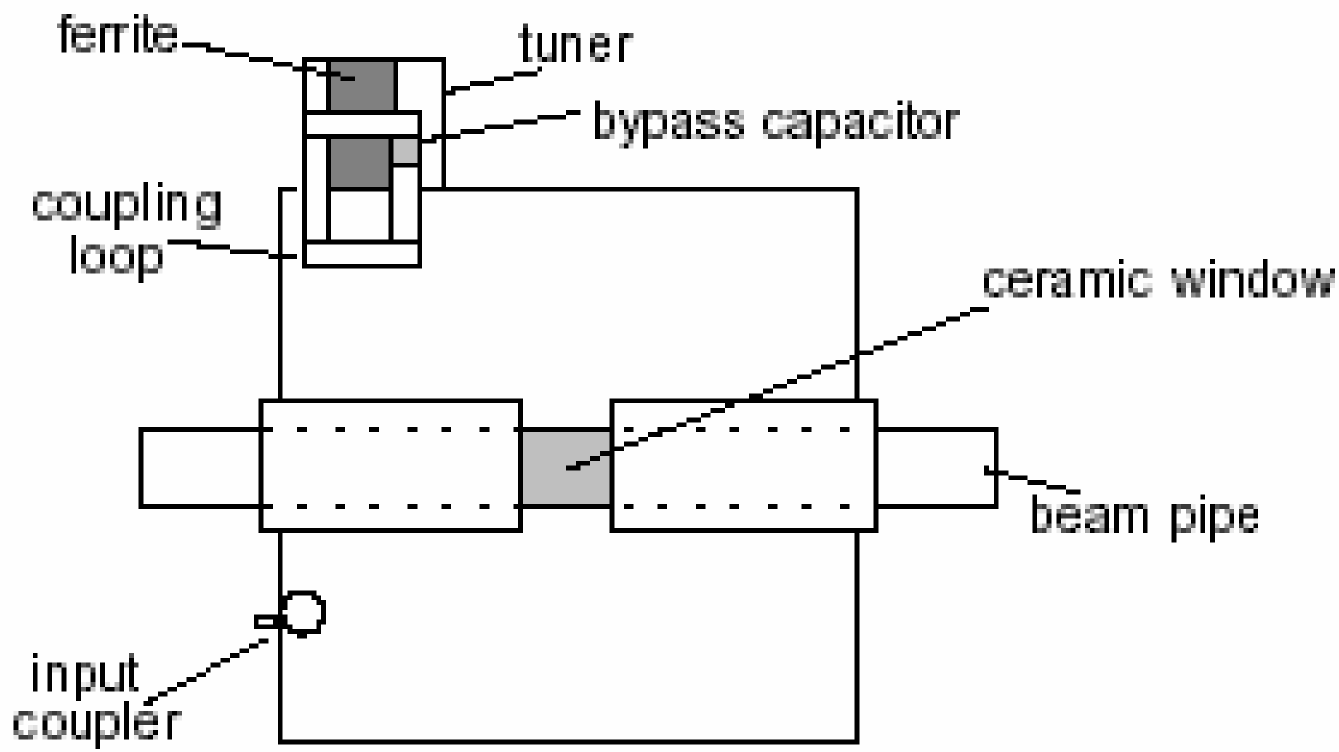


9.8 MHz RF System Block Diagram

PAR 12th Harmonic RF Cavity

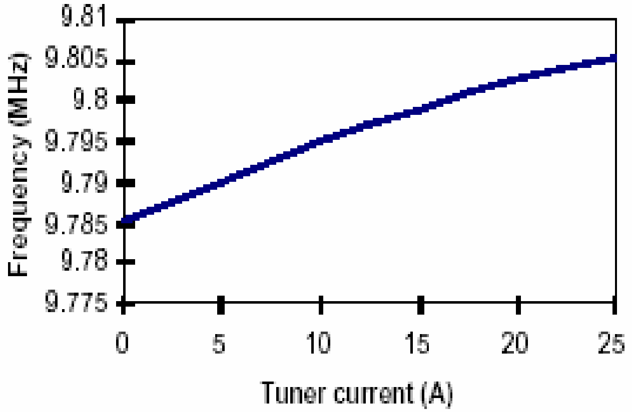


PAR RF Systems

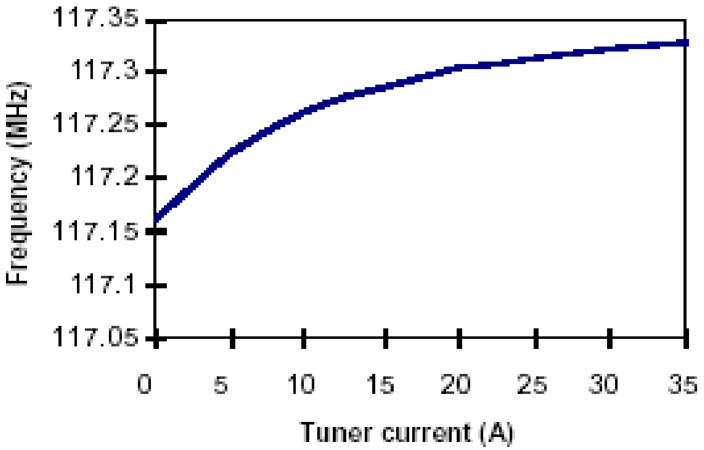


PAR 12th Harmonic Cavity

PAR RF Systems

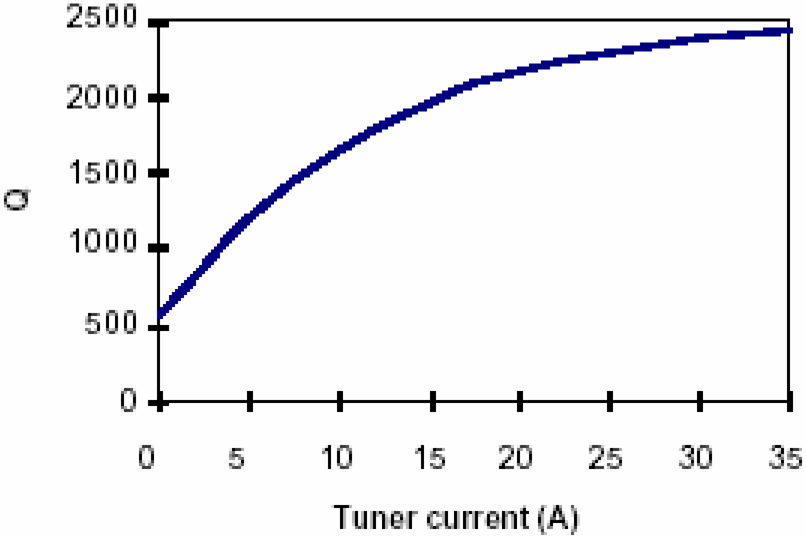


Fundamental Cavity Frequency vs tuner Current

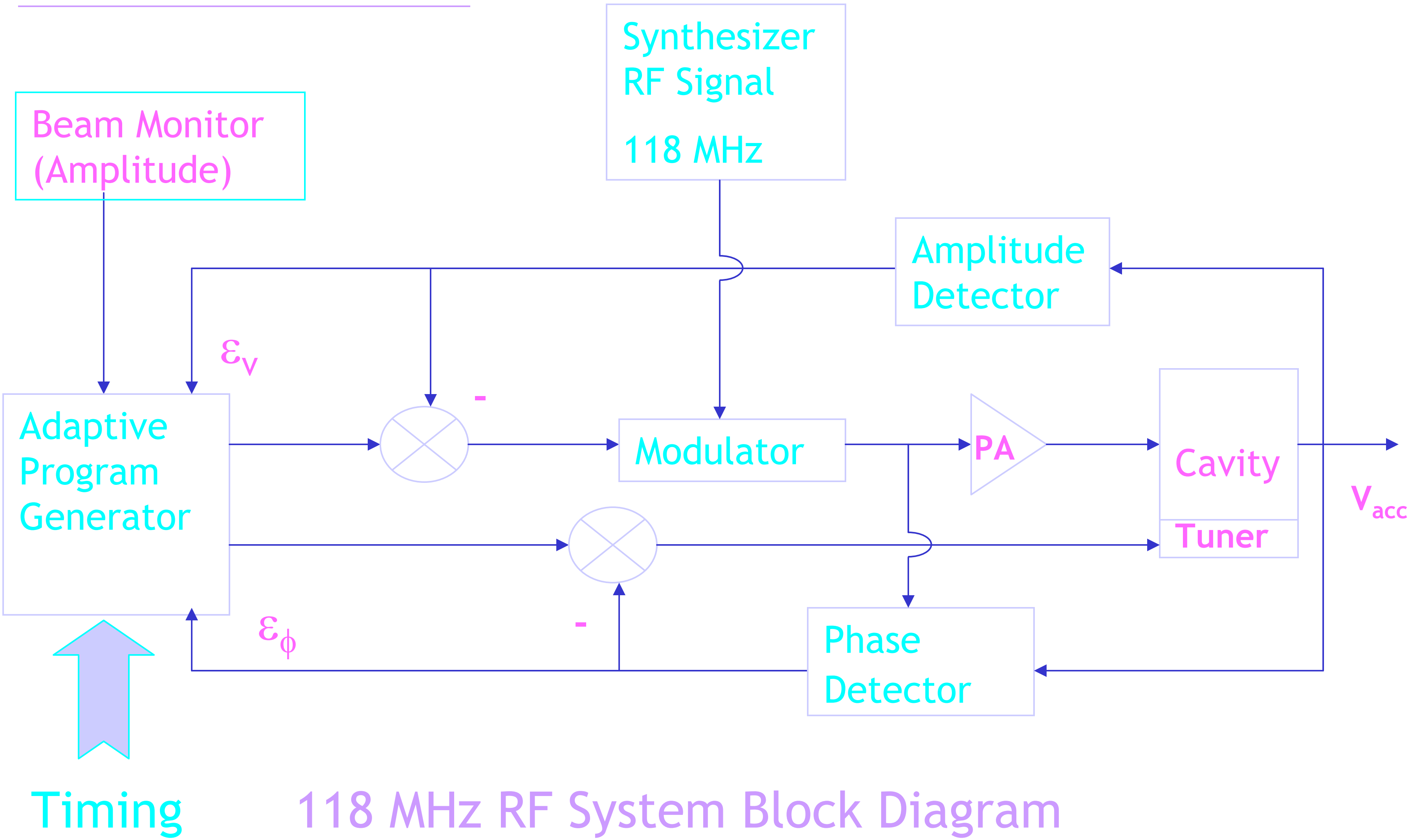


12th Harmonic Cavity Frequency vs tuner Current

12th Harmonic Cavity Q vs. Tuner Current

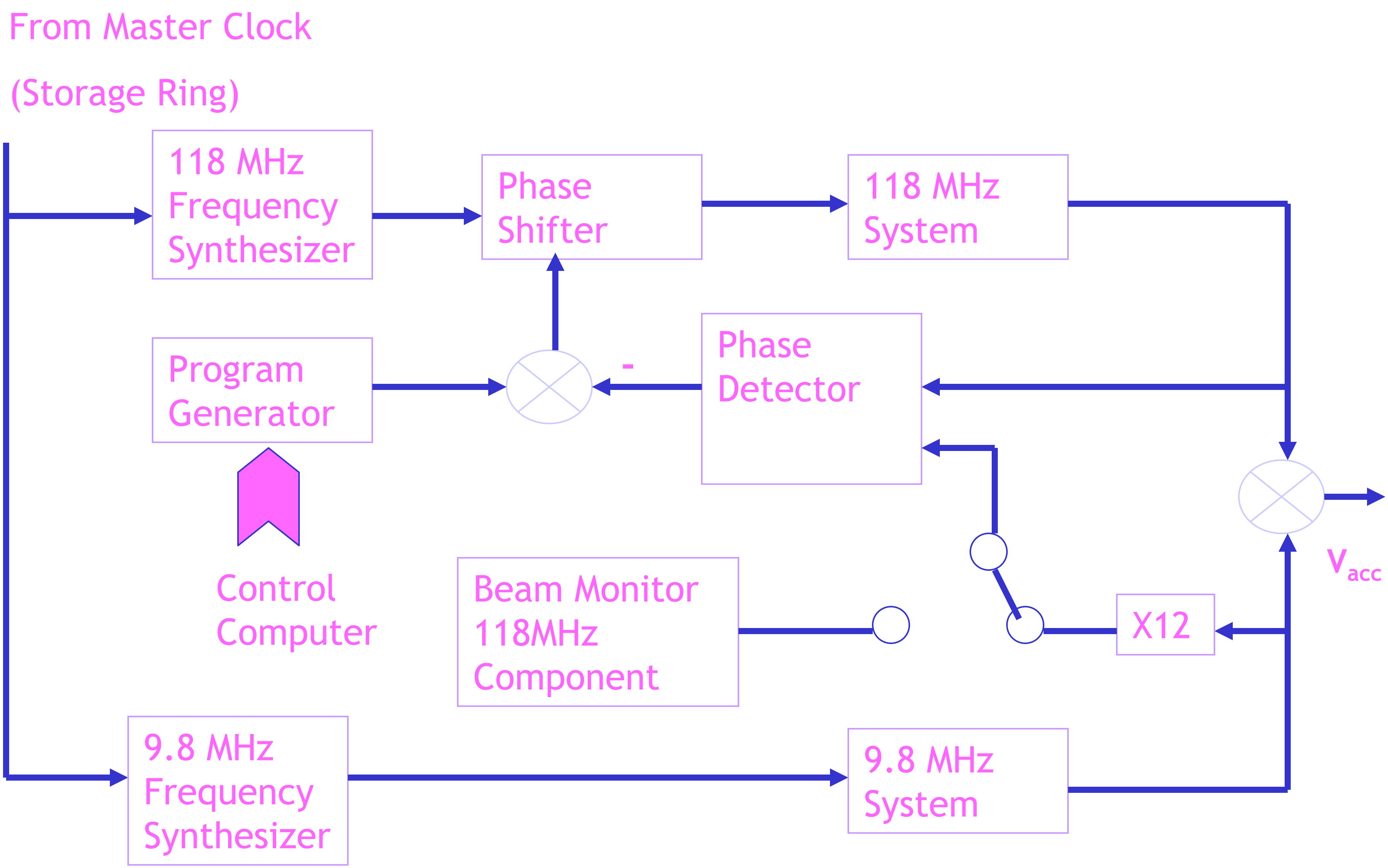


PAR 12th Harmonic

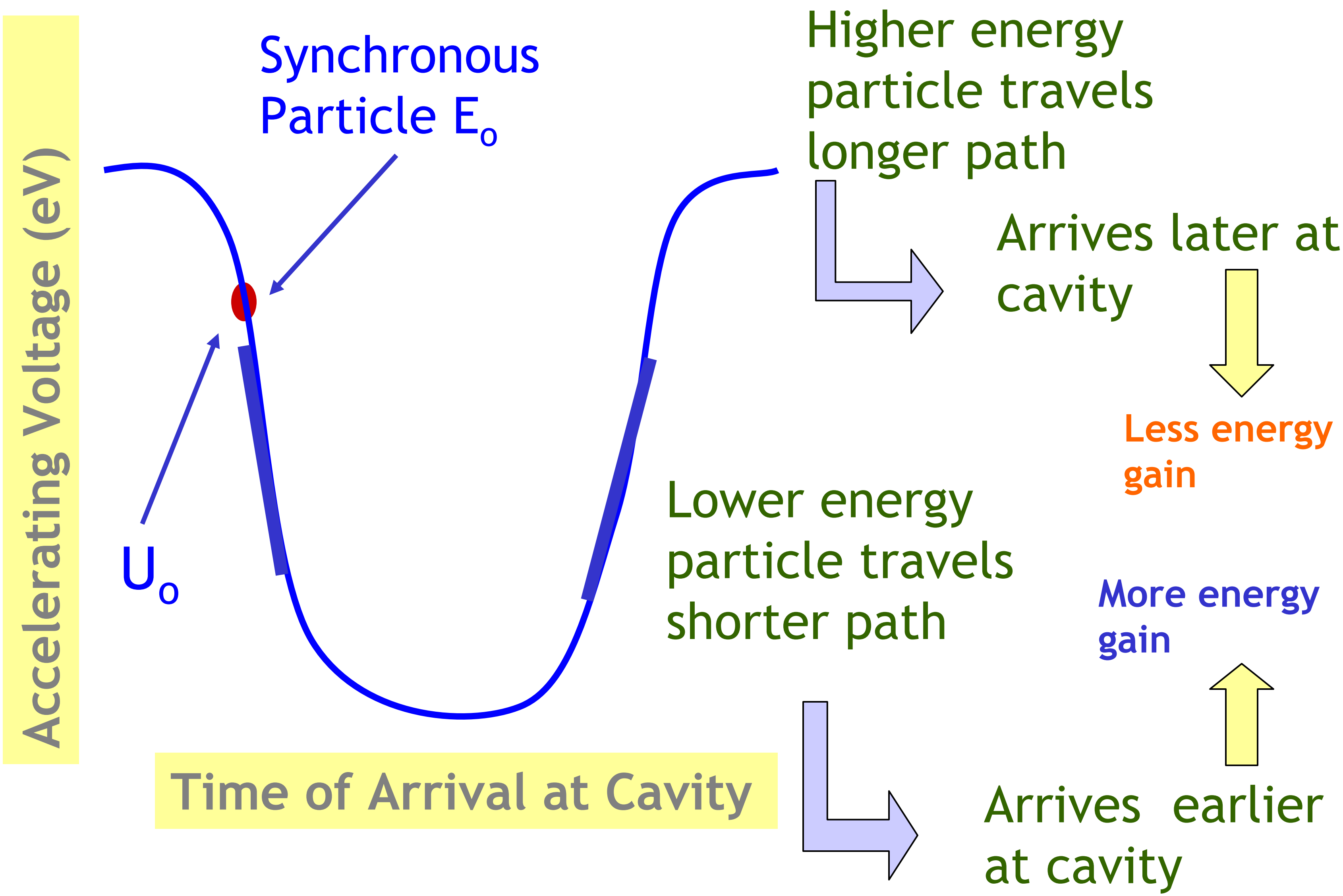


118 MHz RF System Block Diagram

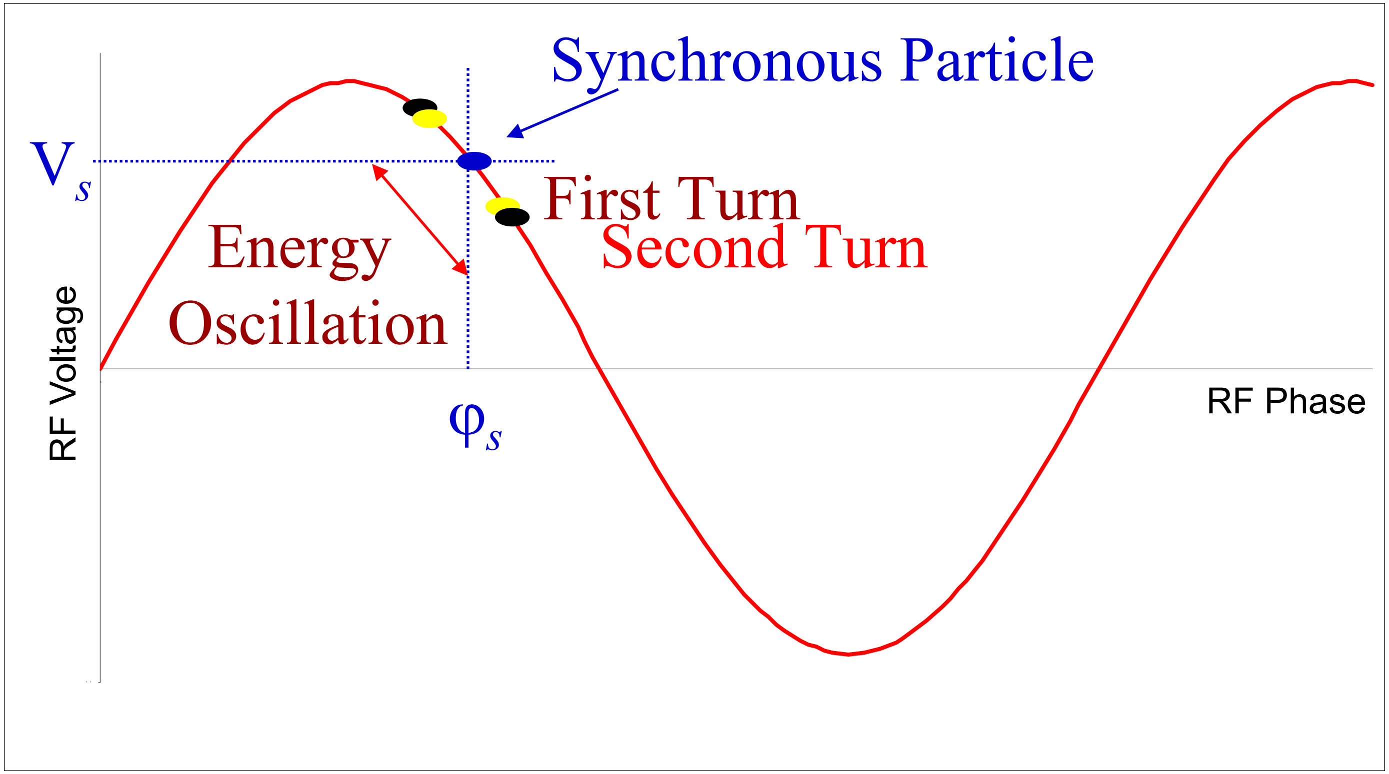
PAR RF Systems Synchronization



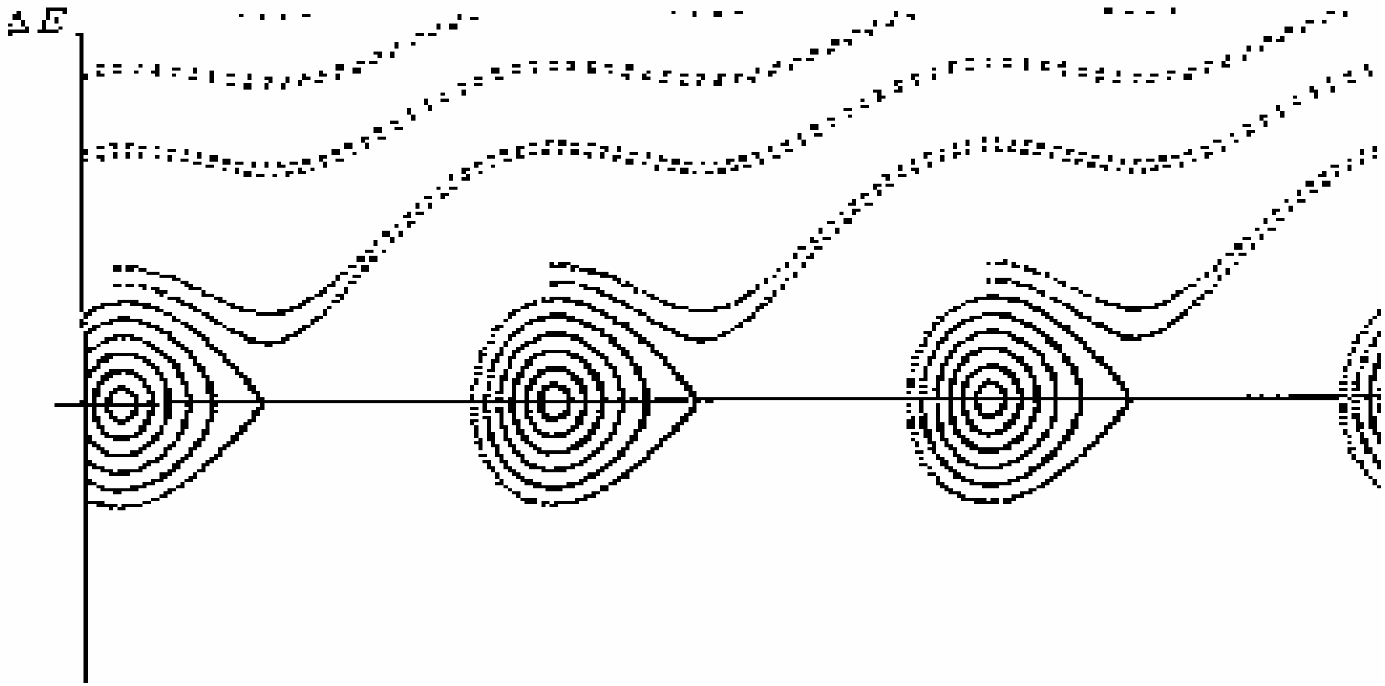
Booster Synchrotron



Booster Synchrotron

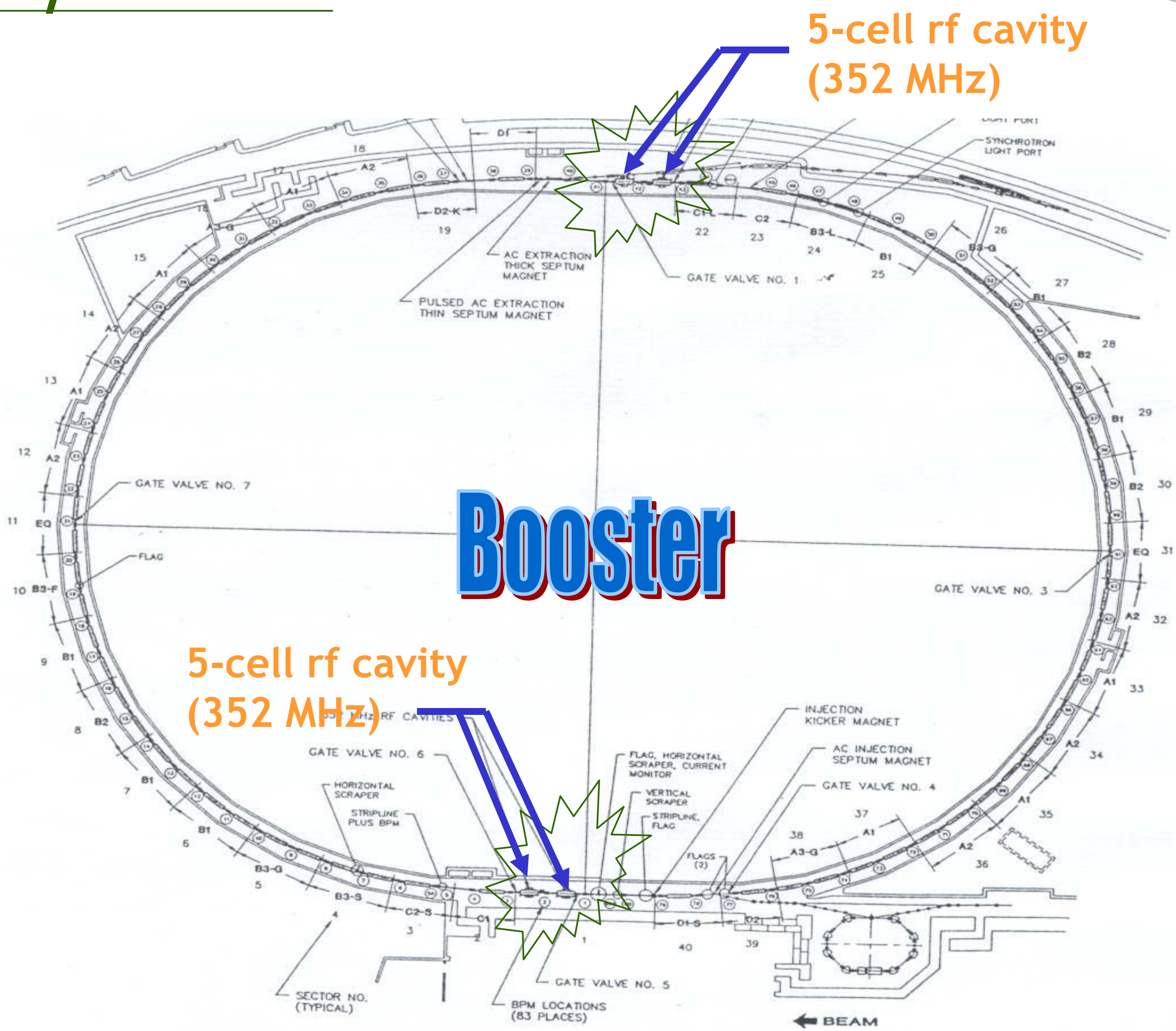


Limit of Stability

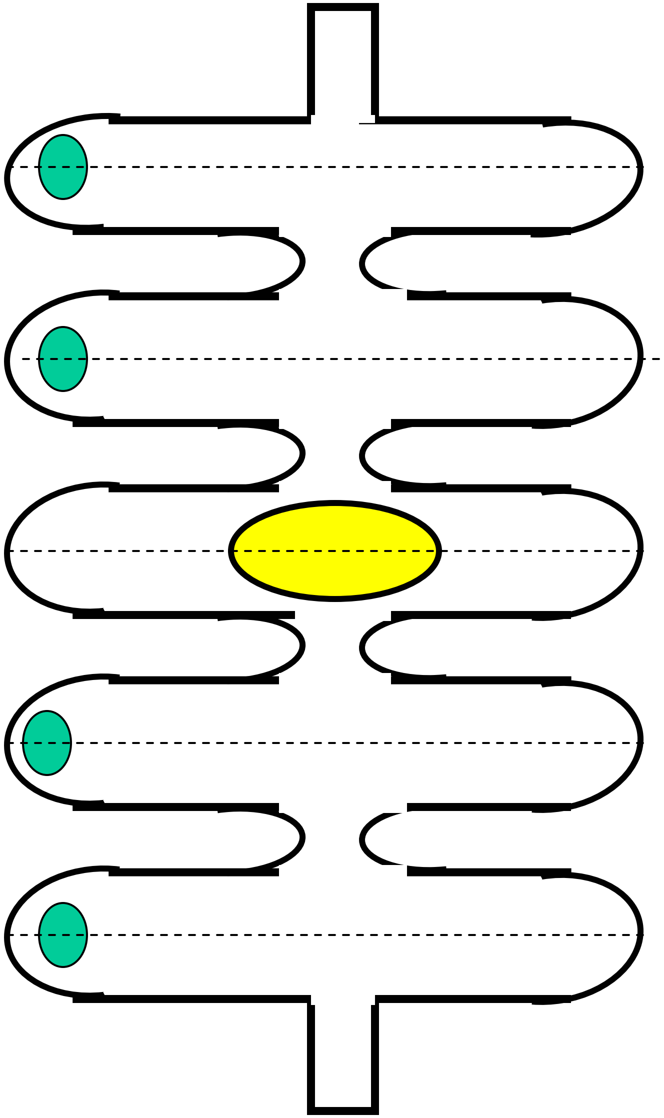


Not all particles are stable. There is a limit to the stable region (the separatrix or "bucket") and, at high intensity, it is important to design the machine so that all particles are confined within this region and are "trapped".

Booster Synchrotron



Booster Synchrotron



Booster 352 MHz 5 cells cavity

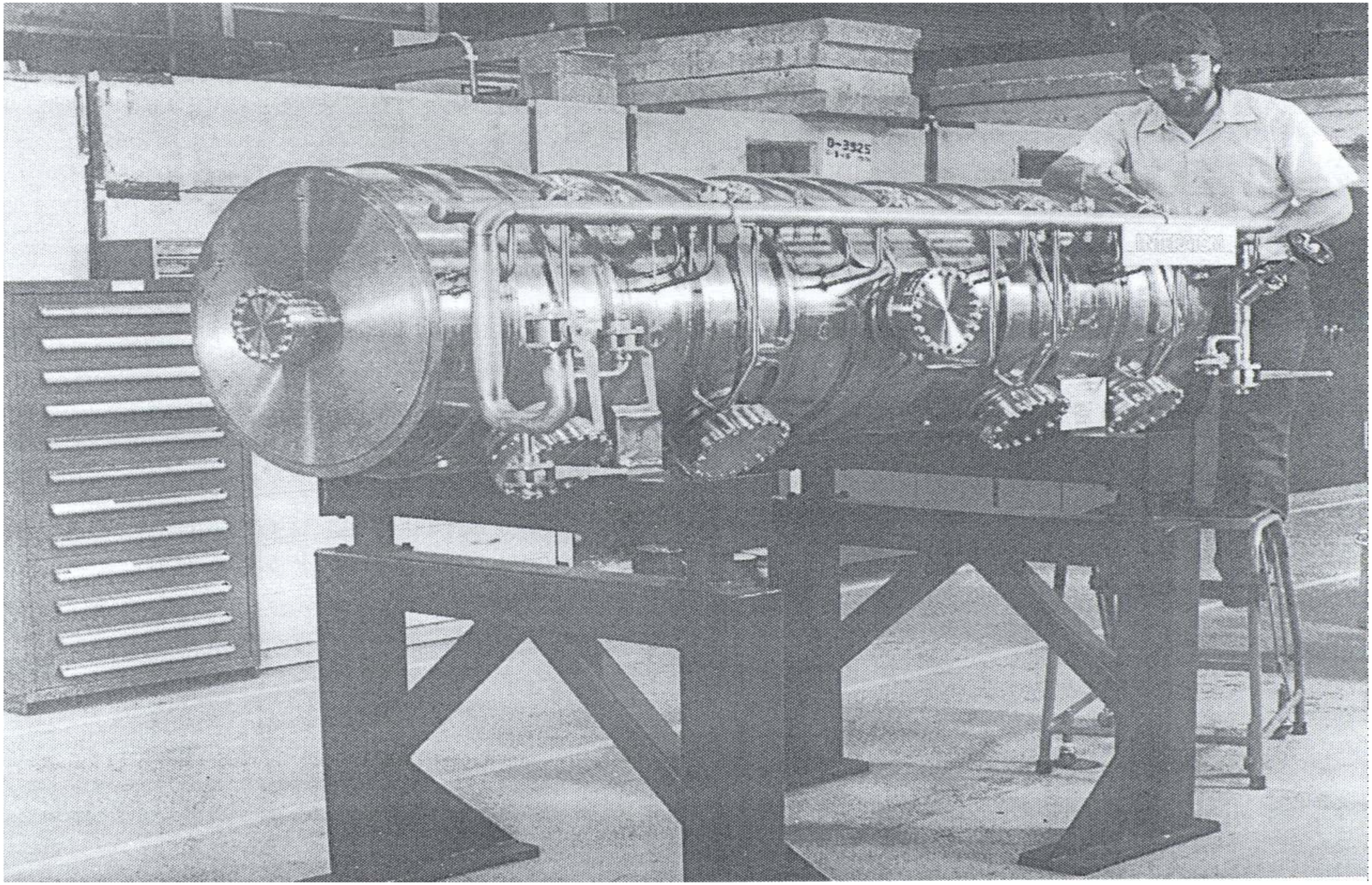
Booster Synchrotron

Five-Cell $\lambda/2$ 352 MHz Booster Cavity

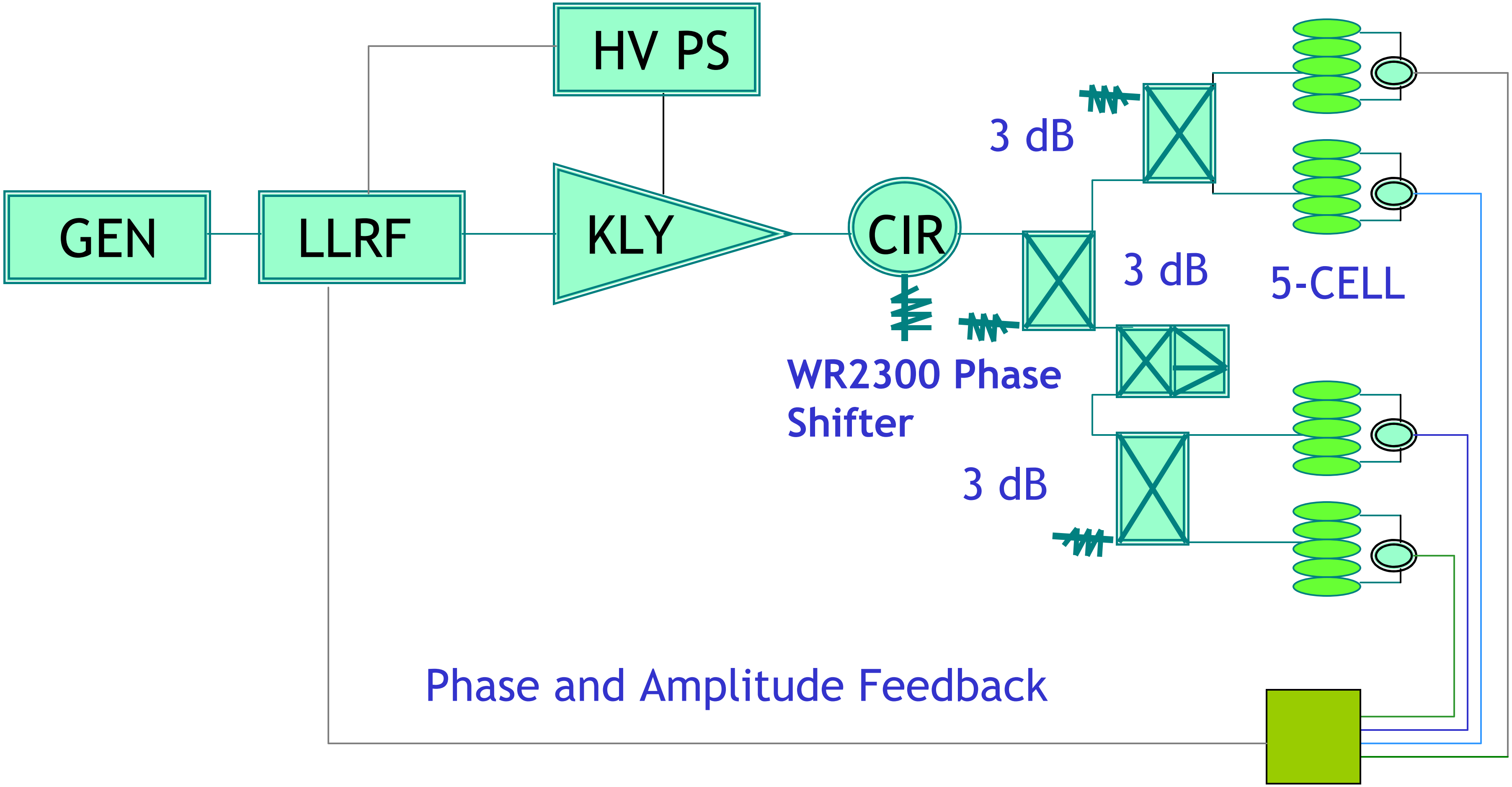
Bore-hole diameter	10 cm
Cell length	42.6 cm
Cell radius	30.2 cm
Total length of cavity	2.32 m
Shunt impedance per cavity	55.3 MΩ
Average accelerating voltage	1.40 MV/m
Total power required	550 kW

Booster Synchrotron

Five-Cell λ/2 352 MHz Booster Cavity



Booster Synchrotron



Booster Synchrotron

The power transferred from the RF to the electron beam is given by

$$P_b(kW) = U_\circ I_b$$

Where I_b is the circulating current in Amps. In addition there is also the power dissipated in the cavity walls given by

$$P_{wall} = \frac{V_{RF}^2}{2 n_c R_{sh}}$$

Where n_c is the number of cavities, R_{sh} is the shunt impedance of a single cavity. Thus the total power to be replenished is $P=P_b+P_{wall}$.

Booster Synchrotron

To achieve zero reflected power in cavities with full beam loading, the RF system should fulfill the following conditions:

a. the reactive component of the beam current should be canceled by properly detuning the cavity so that the beam-loaded cavity is seen as a pure resistance;

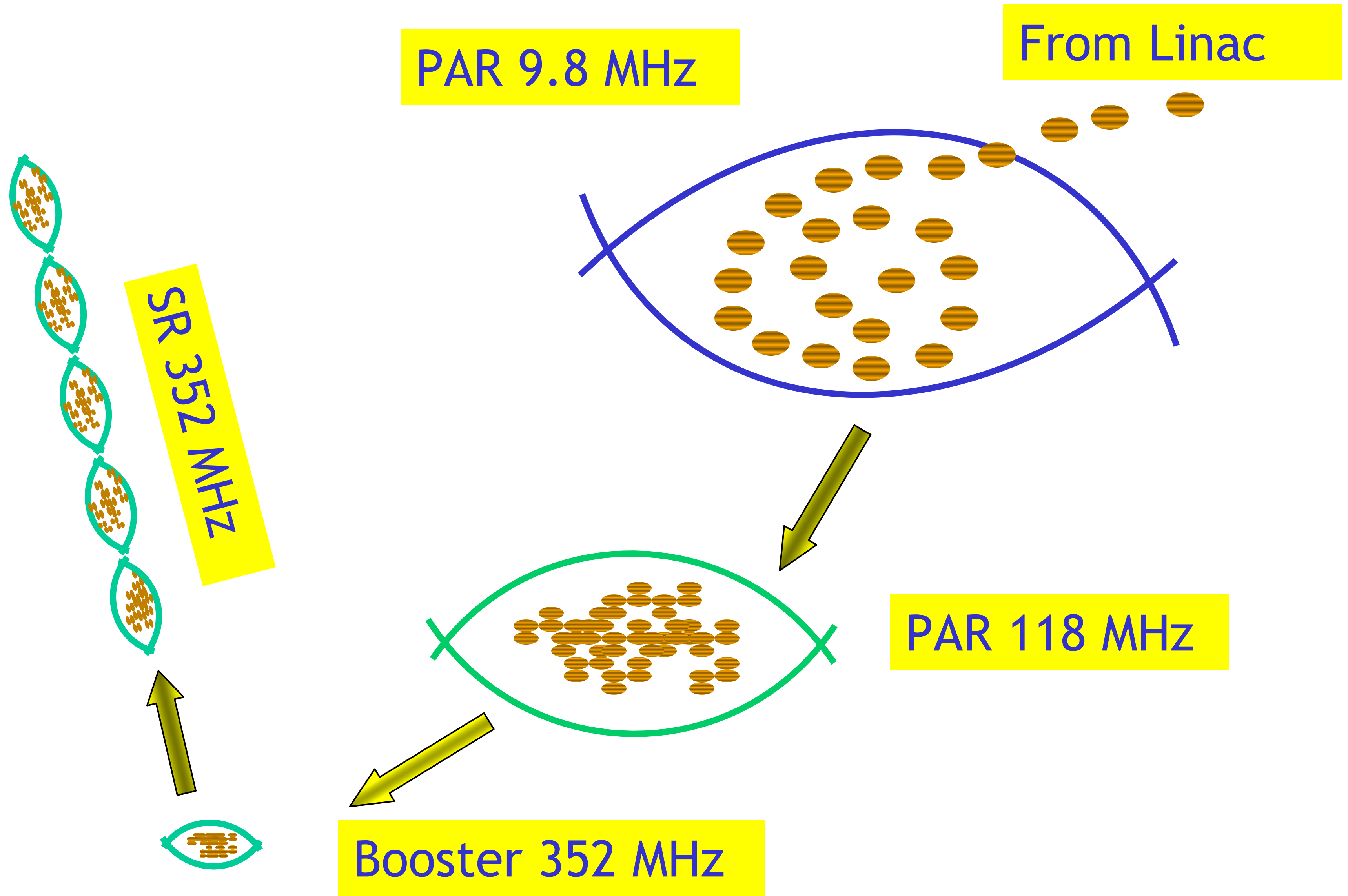
b. this equivalent resistance is matched to the RF source impedance by the correct setting of the coupling factor.

The detuning Δf_m and the coupling factor β_m satisfying the above conditions are given by

$$\Delta f_m = \frac{f_{RF}}{2Q_\circ} \frac{P_b}{P_W} \cot \phi_s$$

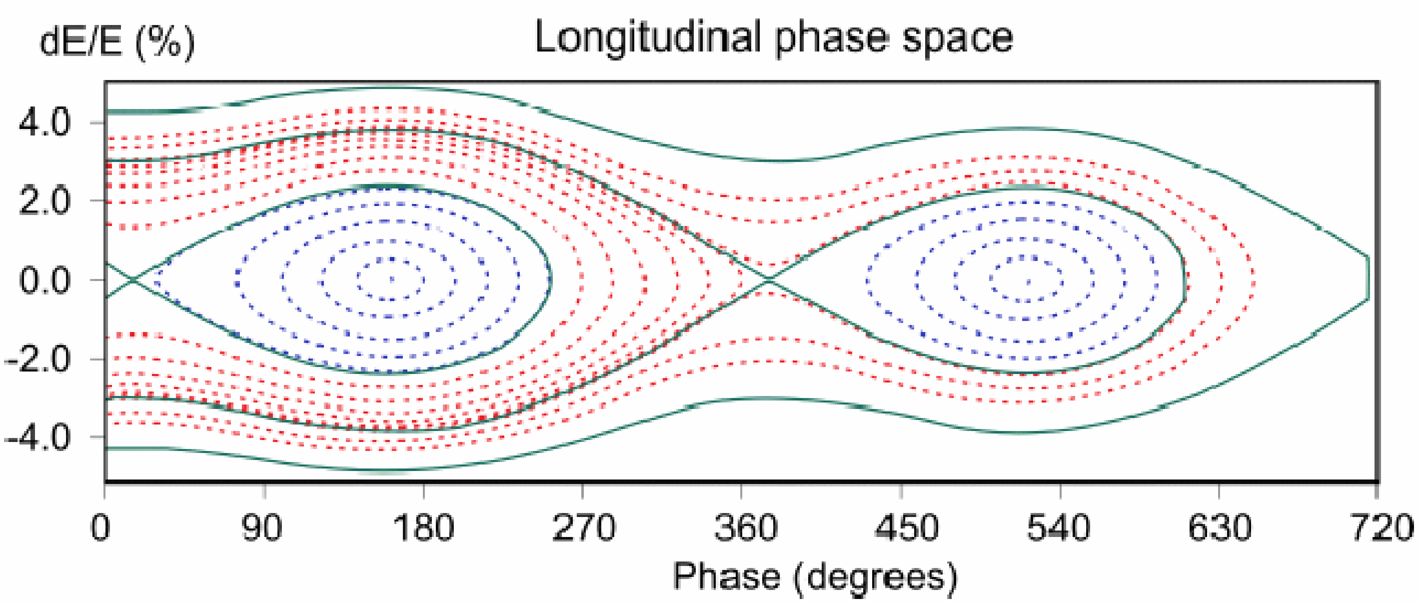
$$\beta_m = 1 + \frac{P_b}{P_W}$$

Booster Synchrotron



Booster Synchrotron

The equilibrium synchronous phase ϕ_s is defined as the phase of the electron beam with respect to the RF accelerating wave when the energy gain by the particle ($eV_{RF}\sin\phi_s$) is equal to the energy lost to synchrotron radiation (U_o) per turn, meaning the synchronous phase should be chosen such that $U_o = eV_{RF} \sin \phi_s$. The convention used for phase is that $\phi_s = 0$ at the zero crossing and the rise of the RF voltage. The stable boarding separatrix in the figure defines the energy acceptance of the stored



Booster Synchrotron

Circumference	368 m
Revolution time	1.228 μs
Max attainable energy	7.7 GeV
Injection energy	400 MeV
Cycle period	500 ms
Acceleration time	250 ms
Circumference	368 m
Average beam current	4.7 mA
Nominal charge per cycle	5.4 nC
Injected beam emittance	0.36 mm-mrad
Natural emittance at 7 GeV	0.13 mm-mrad
Energy loss/turn at 7 GeV	6.3 MeV/turn
RF gap voltage at 7 GeV	8.3 MV

Booster Synchrotron